11 MARCH 1967

K-11-67-1

HANDBOOK OF PHYSICAL AND THERMAL PROPERTY DATA FOR HYDROGEN

TRIPLE POINT REGION TO CRITICAL POINT REGION

A STUDY OF HYDROGEN SLUSH AND/OR HYDROGEN GEL UTILIZATION | VOLUME I

Contract NAS 8-20342

CRYOGENIC STAGE PROGRAMS

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CRYOGENIC STAGE PROGRAMS

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

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MISSILES & SPACE COMPANY

A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

SUNNYVALE CALIFORNIA

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Section 1
INTRODUCTION

The Handbook of Physical and Thermal Property Data for Hydrogen was prepared for the NASA George C. Marshall Space Flight Center (MSFC) under contract NAS 8-20342. This is Volume I of two volumes that constitute the final report for work performed under the MSFC contract. Mr. A. L. Worlund of the Fluid Thermal Systems Branch of the Propulsion and Vehicle Engineering Laboratory (R-P&VE-PTF) was the technical manager at MSFC for this effort. The primary purpose of presenting these data in handbook form is to provide a convenient source of consistent data for physical and thermal properties of hydrogen, with emphasis on the triple-point region.

This volume is the first known compilation of slush hydrogen properties presented in a format convenient to space-vehicle designers. The increased density and storability of hydrogen propellant, with use of subcooled liquid and slush, warrant incorporation of these data into a single-source book. Data presented were selected after a thorough search of all literature presently available.

All property data are presented in both the English and International systems of units. This not only satisfies a contractural requirement, but also provides convenient, reliable data for designers working with either system. Conversion factors are presented in Section 5.

During performance of this contract program, close coordination was maintained with Mr. D. B. Mann and Mr. D. B. Chelton of the Cyrogenics Division of the National Bureau of Standards (NBS) Institute for Materials Research, where a related analytical and experimental program is in progress. Figure 1-1 shows a mixture of liquid and solid hydrogen under study in that program. This photograph was taken by NBS after the mixture had aged approximately 40 hr.

Fig. 1-1 Liquid-Solid Hydrogen Mixture (Age: 40 hr 15 min)
(From NBS Report 8881)

Physical and thermal property data in the solid, liquid, and vapor states near the triple-point temperature of 13.803° K (24.85° R) were used from this data book in performing the hydrogen slush utilization contract study. Nearly all properties presented were selected for parahydrogen, since this is the major component of low-temperature equilibrium mixtures. However, certain properties, such as the solubility of helium in hydrogen, exhibit significantly different properties for parahydrogen and orthohydrogen in the region near the critical-point. Therefore, this property was presented for equilibrium mixtures whose properties are shown in Figs. 2-1 and 3-1.

Section 2

PHYSICAL-THERMAL PROPERTIES OF HYDROGEN IN ENGLISH UNITS

Physical and thermal property data for hydrogen in the regions between the triple-point and the critical-point are presented in the English system of units in the following table and illustrations.

Table 2-1

REFERENCE-POINT PROPERTIES
(English Units)

Physical Property	Triple Point	One Atmosphere	Critical Point
Parahydrogen, Percent	99.789(a)	99.789(b)	94.55 (c)
Temperature, °R	24.85	36.48	59.36
Pressure, psia	1.021	14.6959	187.50
Enthalpy, Btu/lb			
Saturated Vapor	60.3	81.4	16.40
Saturated Liquid	-132.8	-110.2	16.50
Density, lb/ft^3			
Saturated Liquid	4.808	4.425	1.963
50% Liquid – 50% Solid	5.09	(d)	(d)
100% Solid	5.463	(d)	(d)
Saturated Vapor	0.008	0.084	1.963
Viscosity, lb/hr ft			
Vapor at 10 cm Hg	(d)	(d)	(d)
Saturated Liquid	(e)	(0.032)(c)	(0.010)(c)
Surface Tension, lb/ft	2.049	1.323	0.0
Dielectric Constant			
Saturated Vapor	1.0004	1.0040	1.09733
Saturated Liquid	1.2503	1.2285	1.1267(c)
Solid	(1.2505)(c)	(d)	(d)
Compressibility Factor			
Saturated Vapor	0.9838(f)	0.9060(f)	0.3024(f)

(a) This value is suitable due to the time required to reach equilibrium.
(b) At temperature 0.6% off one atmosphere saturated temperature.
(c) Either read from plot or interpolated.
(d) Not applicable.
(e) No data given or uncertain conditions
(f) Calculated using referenced properties.

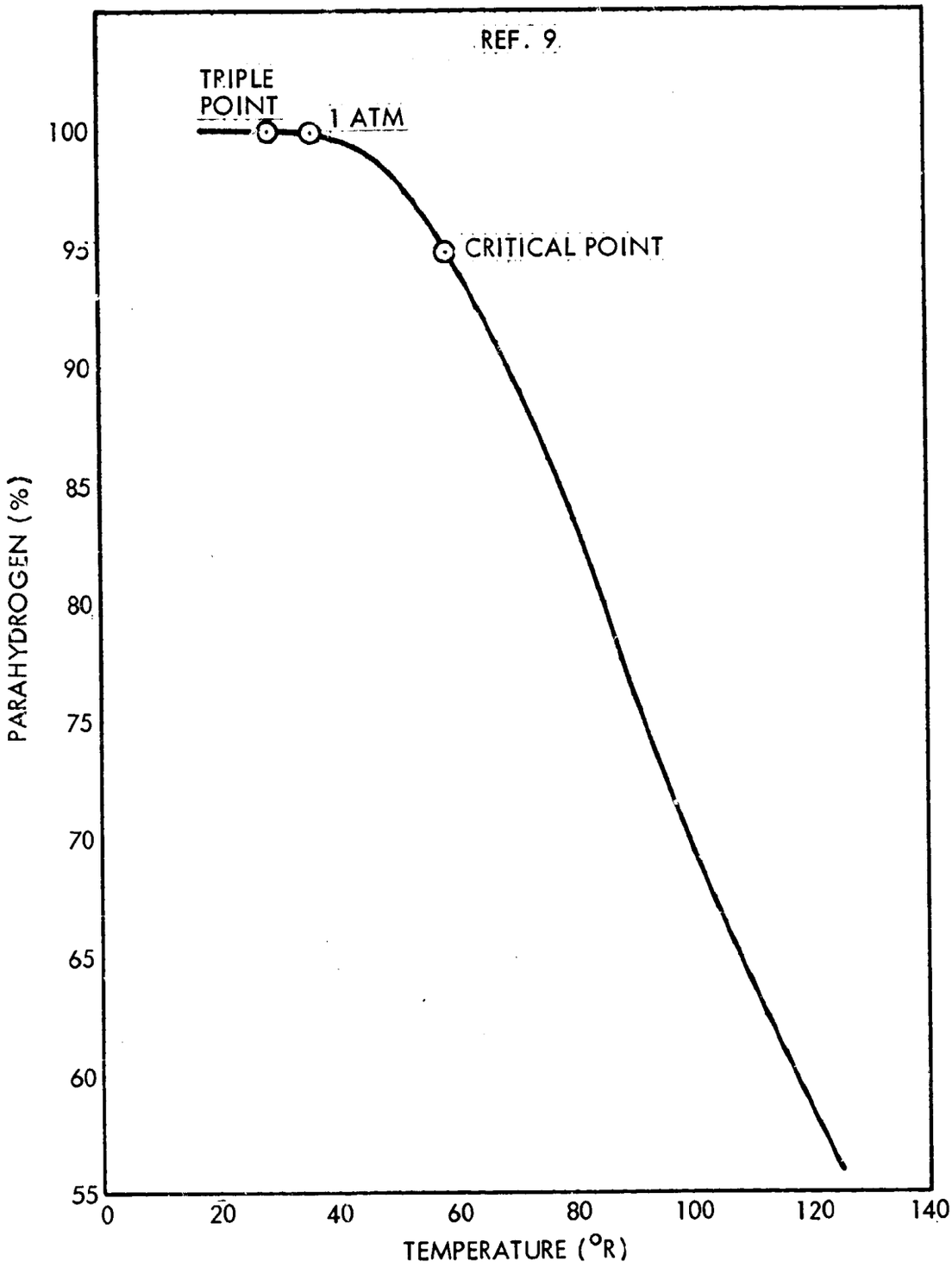

Fig. 2-1 Parahydrogen Composition of Ortho-para Mixture at Equilibrium

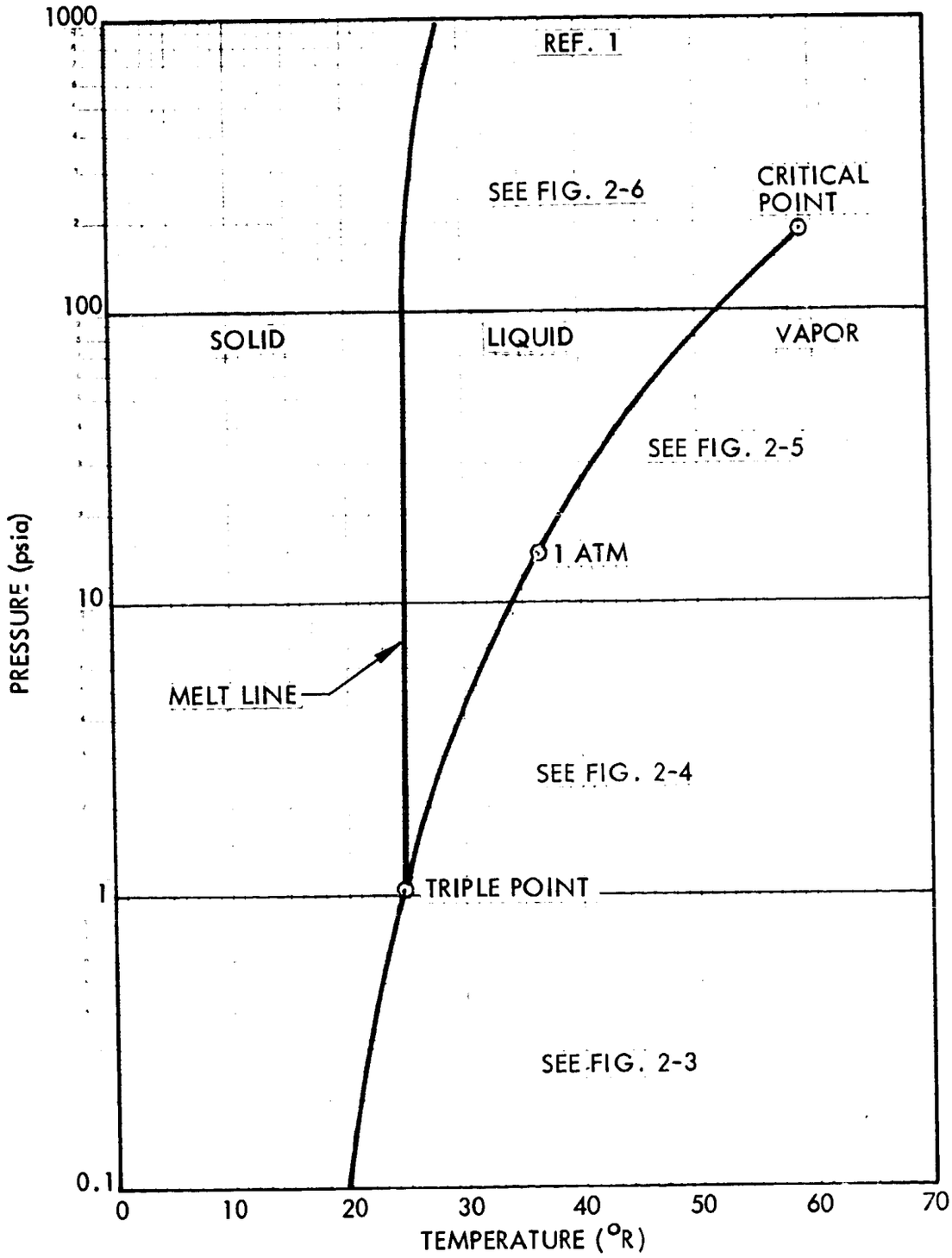

Fig. 2-2 Parahydrogen Pressure-Temperature Phase Diagram

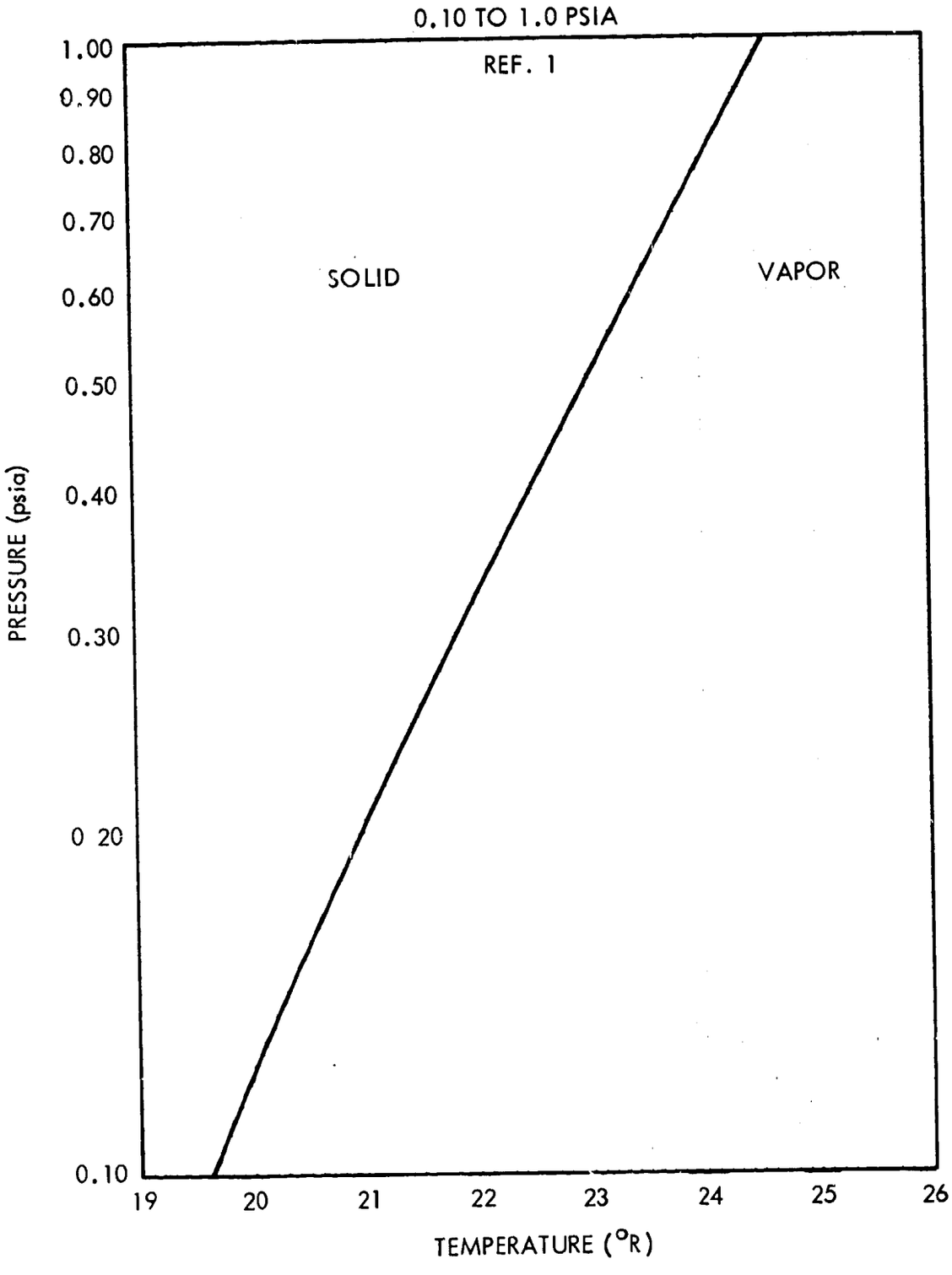

Fig. 2-3 Parahydrogen Pressure-Temperature Phase Diagram (0.1 to 1.0 psia)

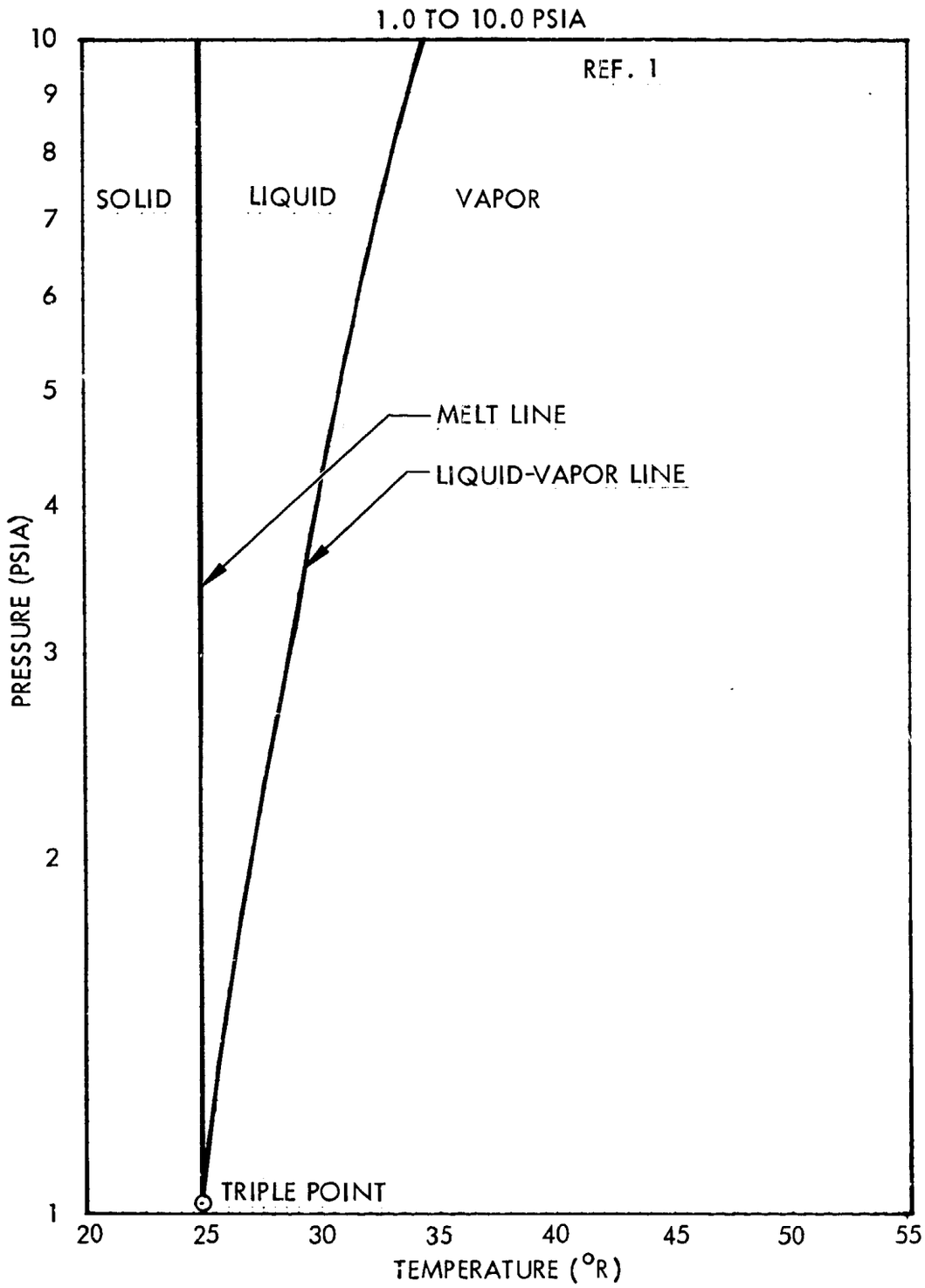

Fig. 2-4 Parahydrogen Pressure-Temperature Phase Diagram (1.0 to 10.0 psia)

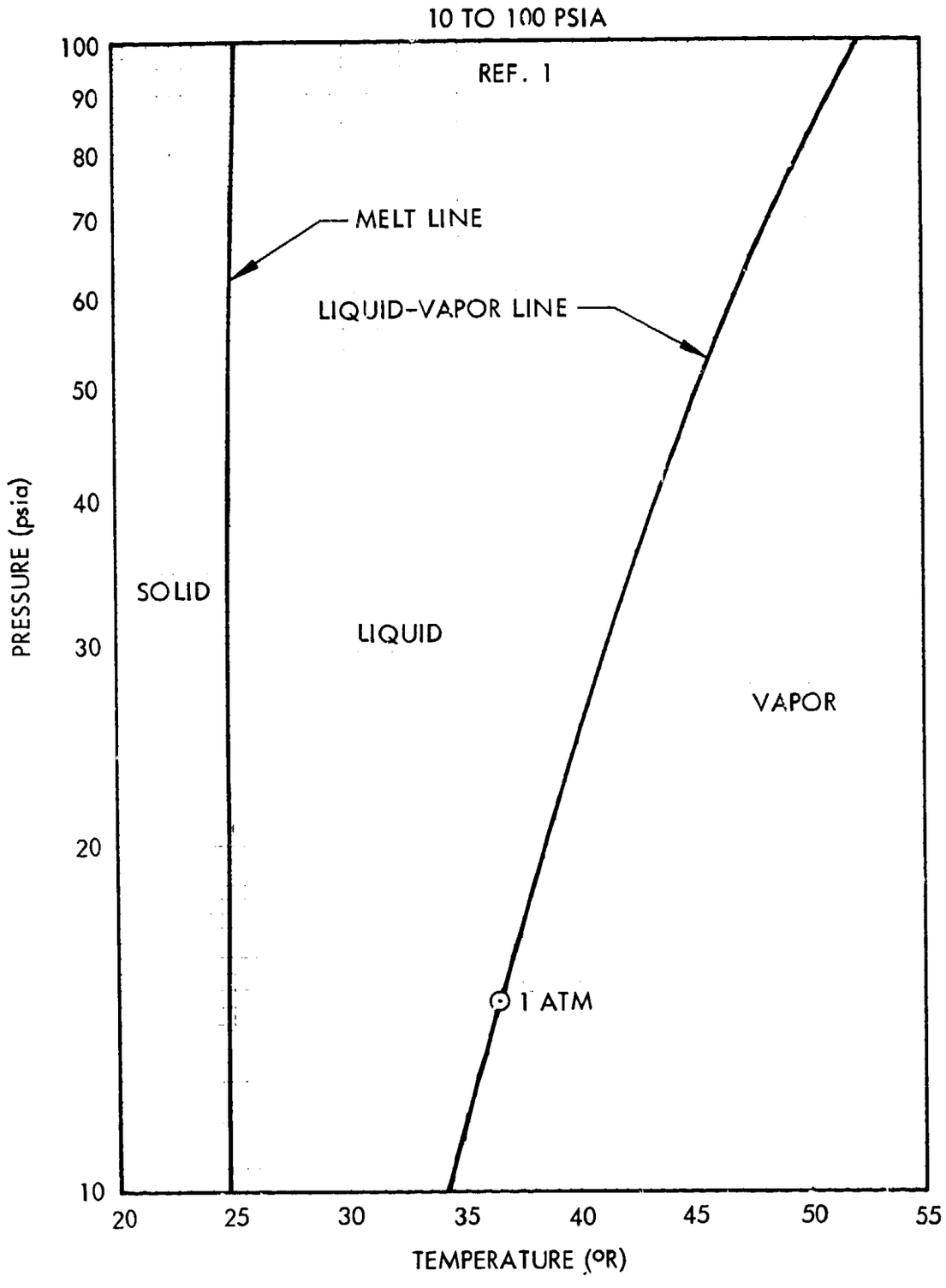

Fig. 2-5 Parahydrogen Pressure-Temperature Phase Diagram (10 to 100 psia)

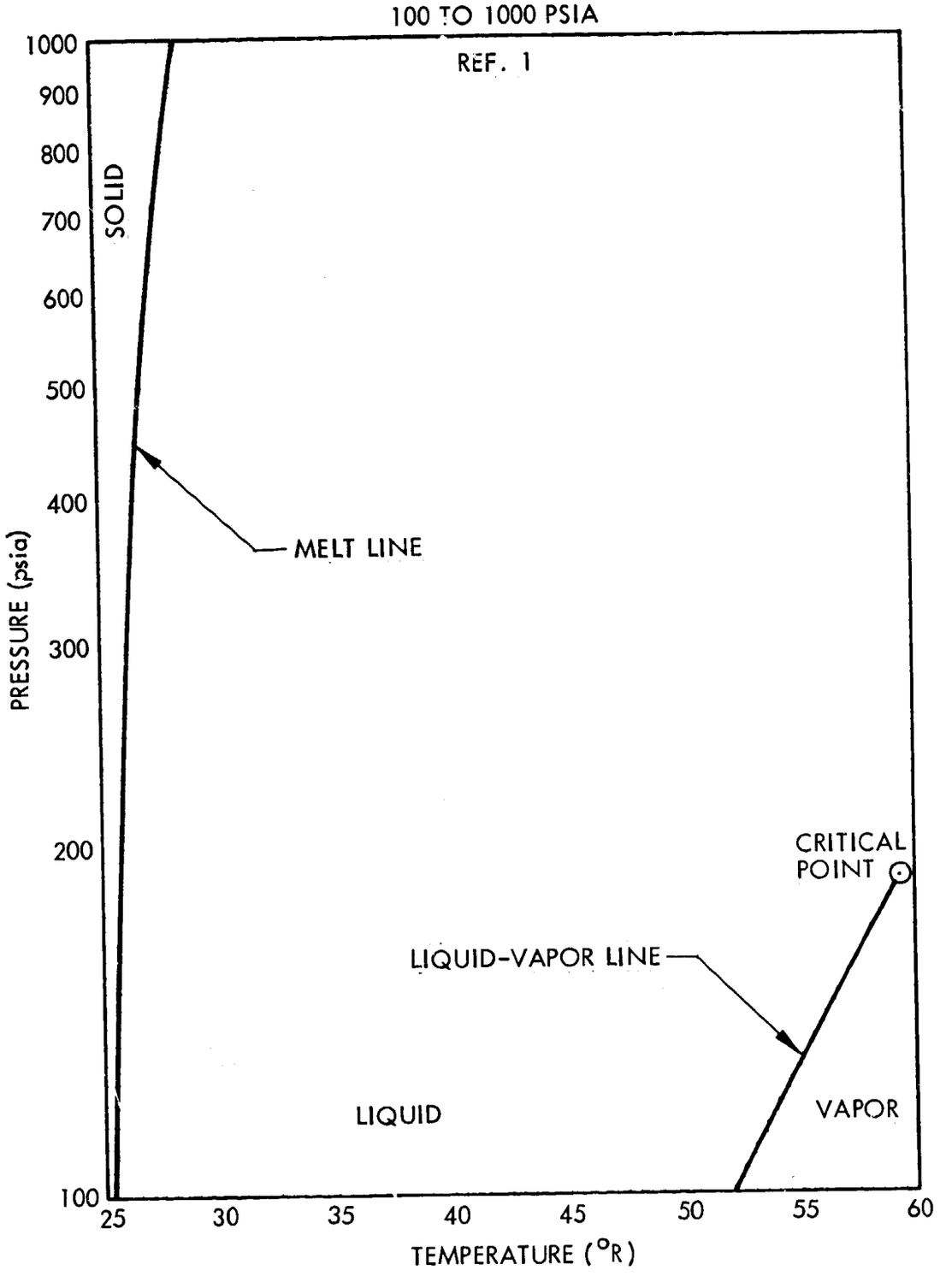

Fig. 2-6 Parahydrogen Pressure-Temperature Phase Diagram (100 to 1000 psia)

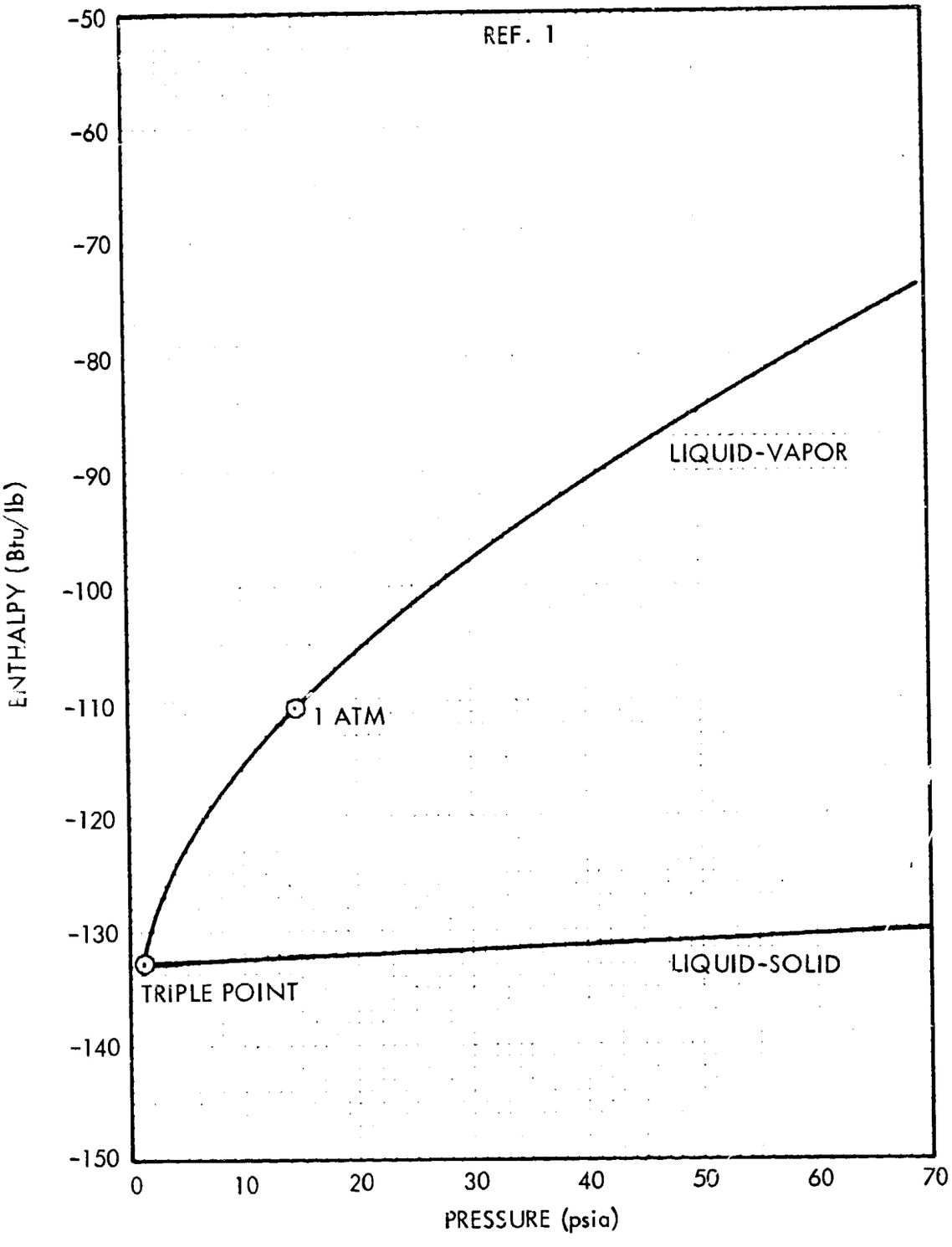

Fig. 2-7 Enthalpy of Saturated Parahydrogen Liquid

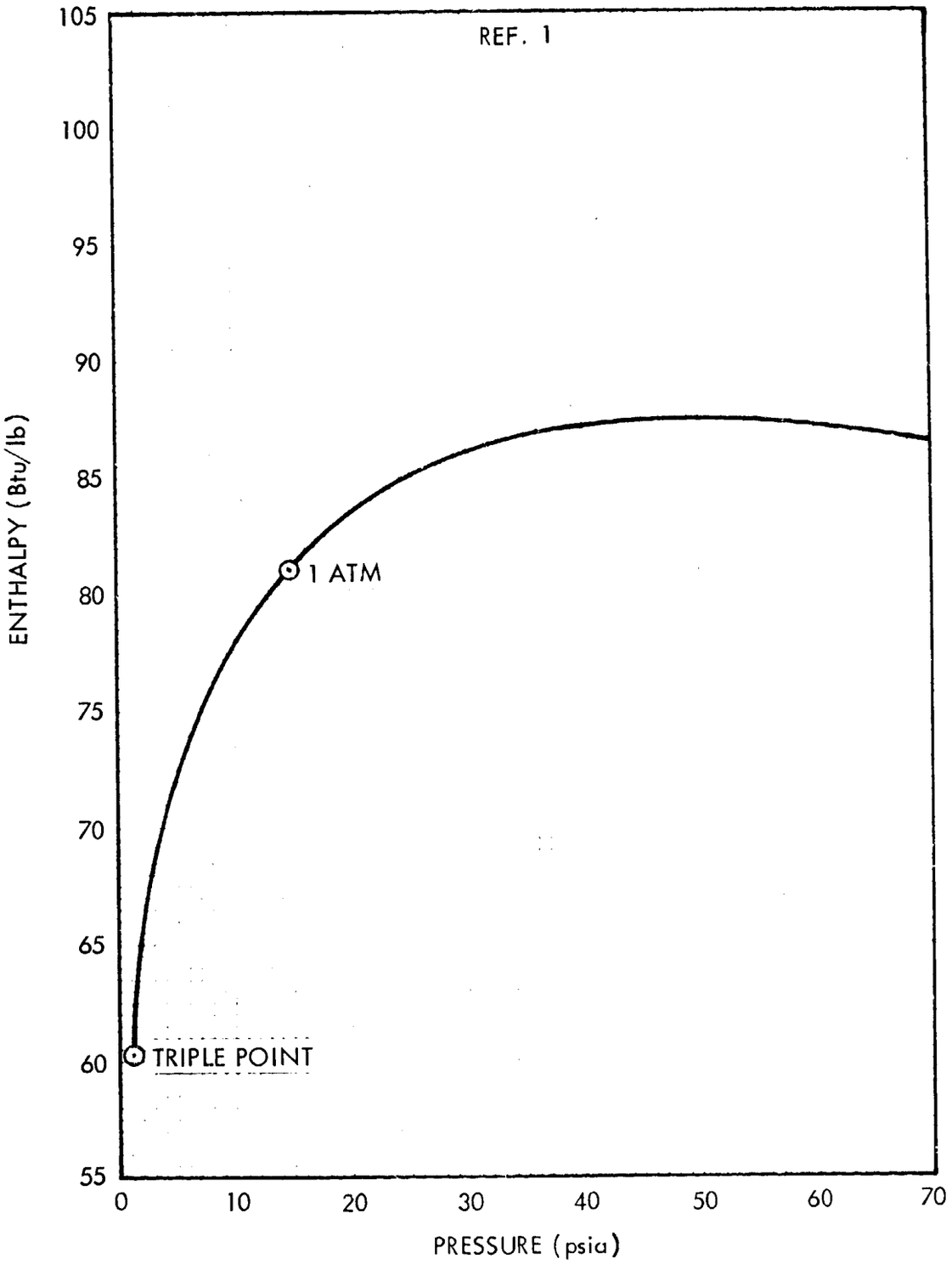

Fig. 2-8 Enthalpy of Saturated Parahydrogen Vapor

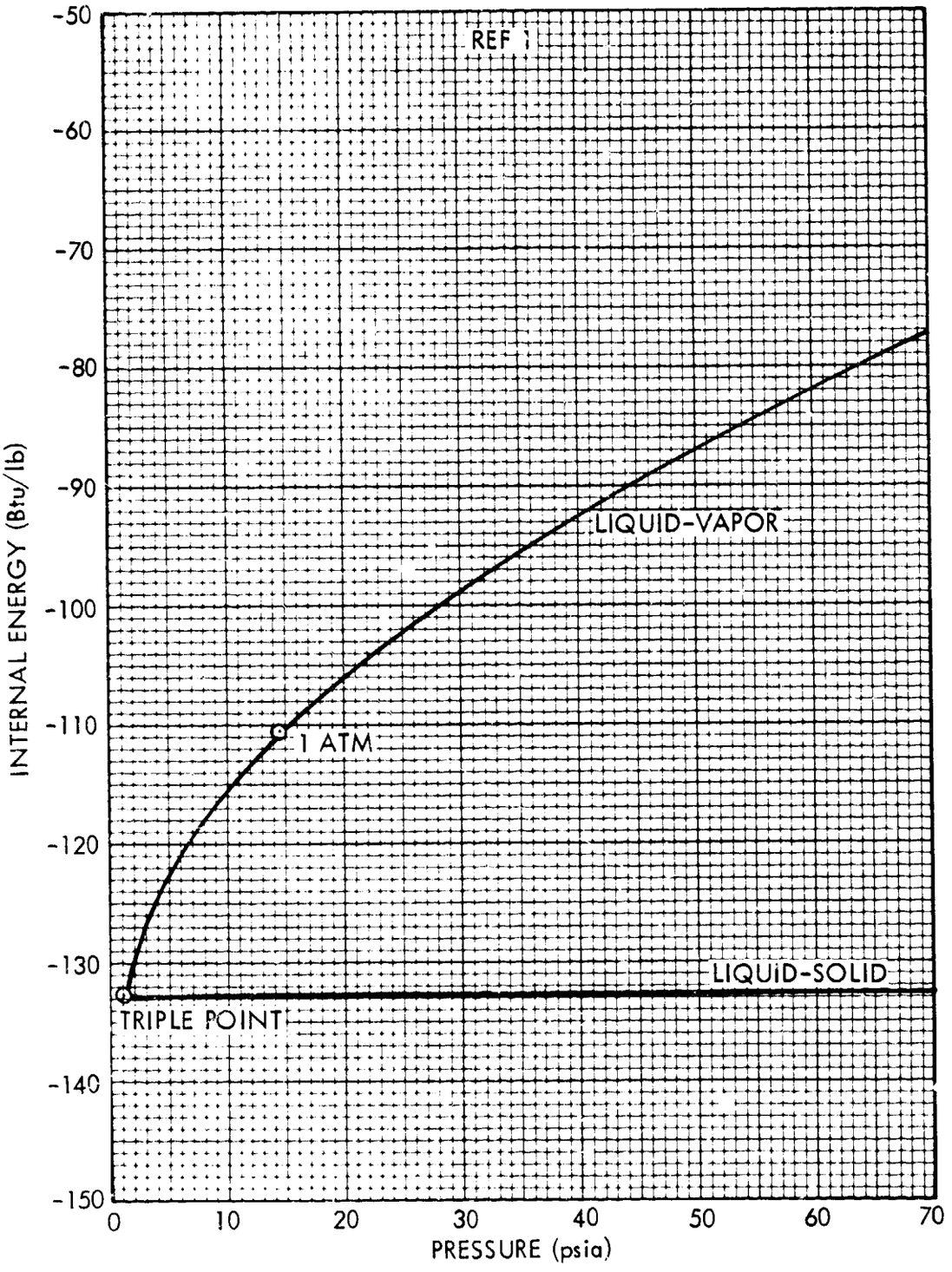

Fig. 2-9 Internal Energy of Saturated Parahydrogen Liquid

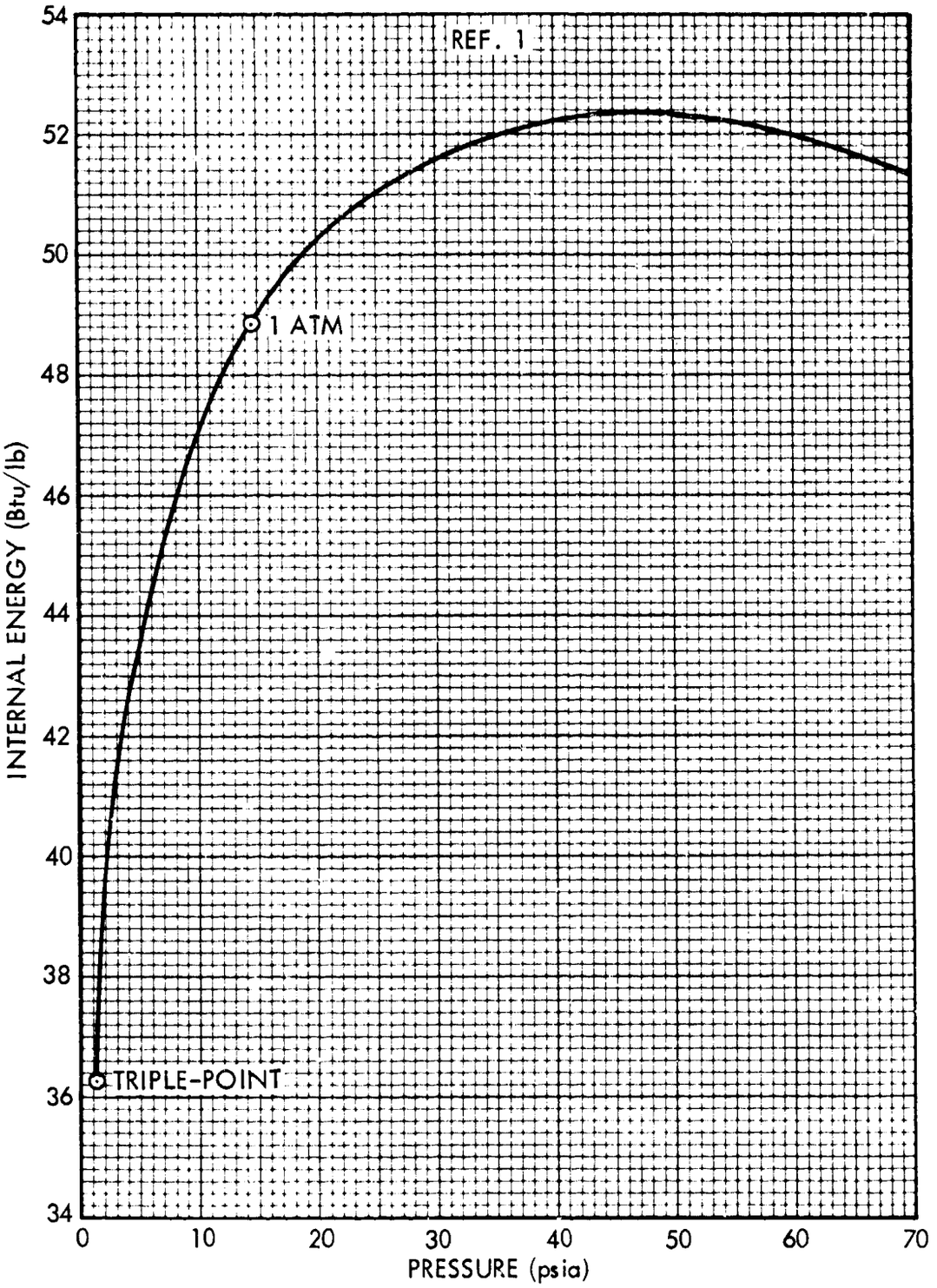

Fig. 2-10 Internal Energy of Saturated Parahydrogen Vapor

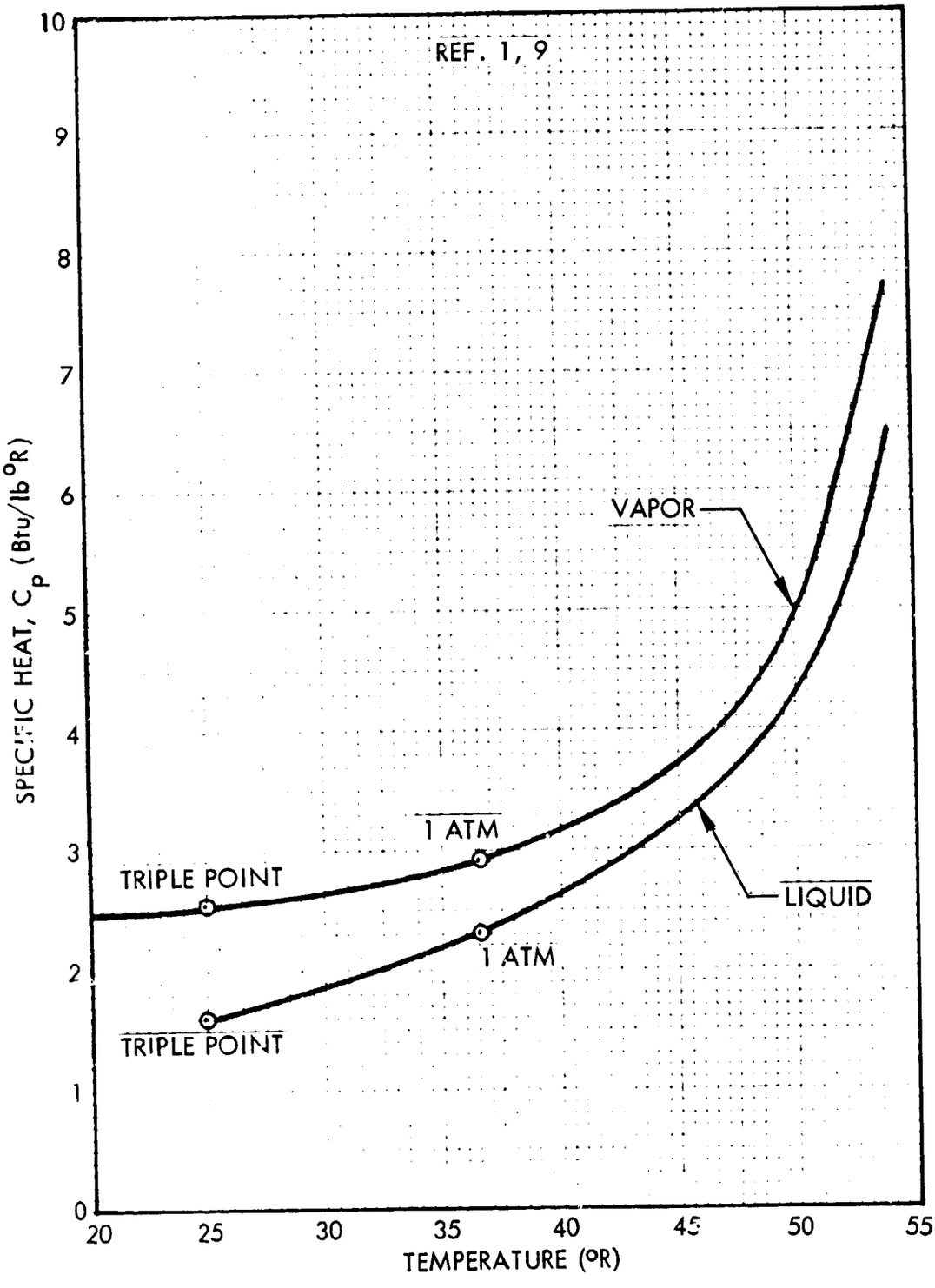

Fig. 2-11 Heat Capacity of Saturated Parahydrogen at Constant Pressure

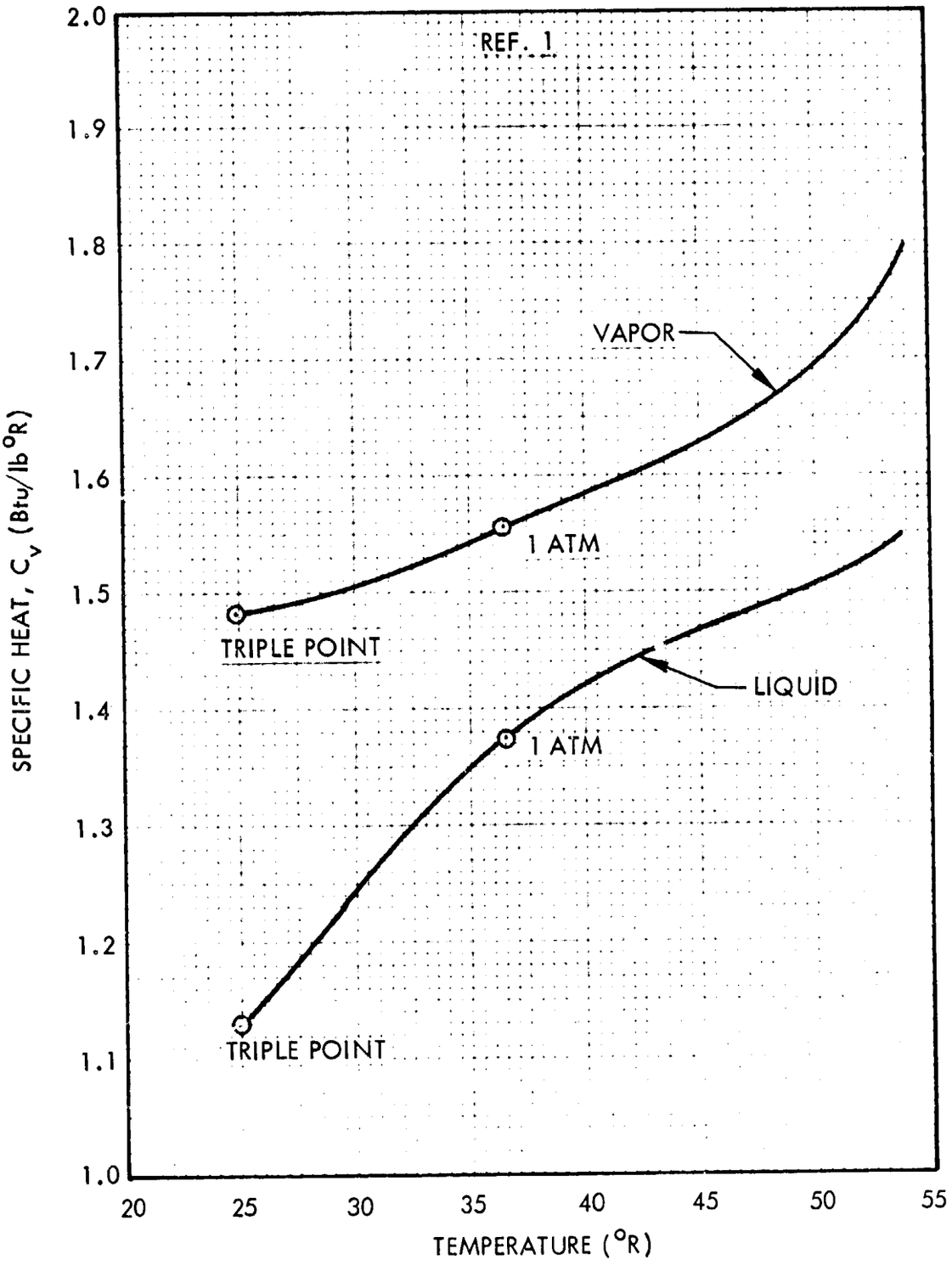

Fig. 2-12 Heat Capacity of Saturated Parahydrogen at Constant Volume

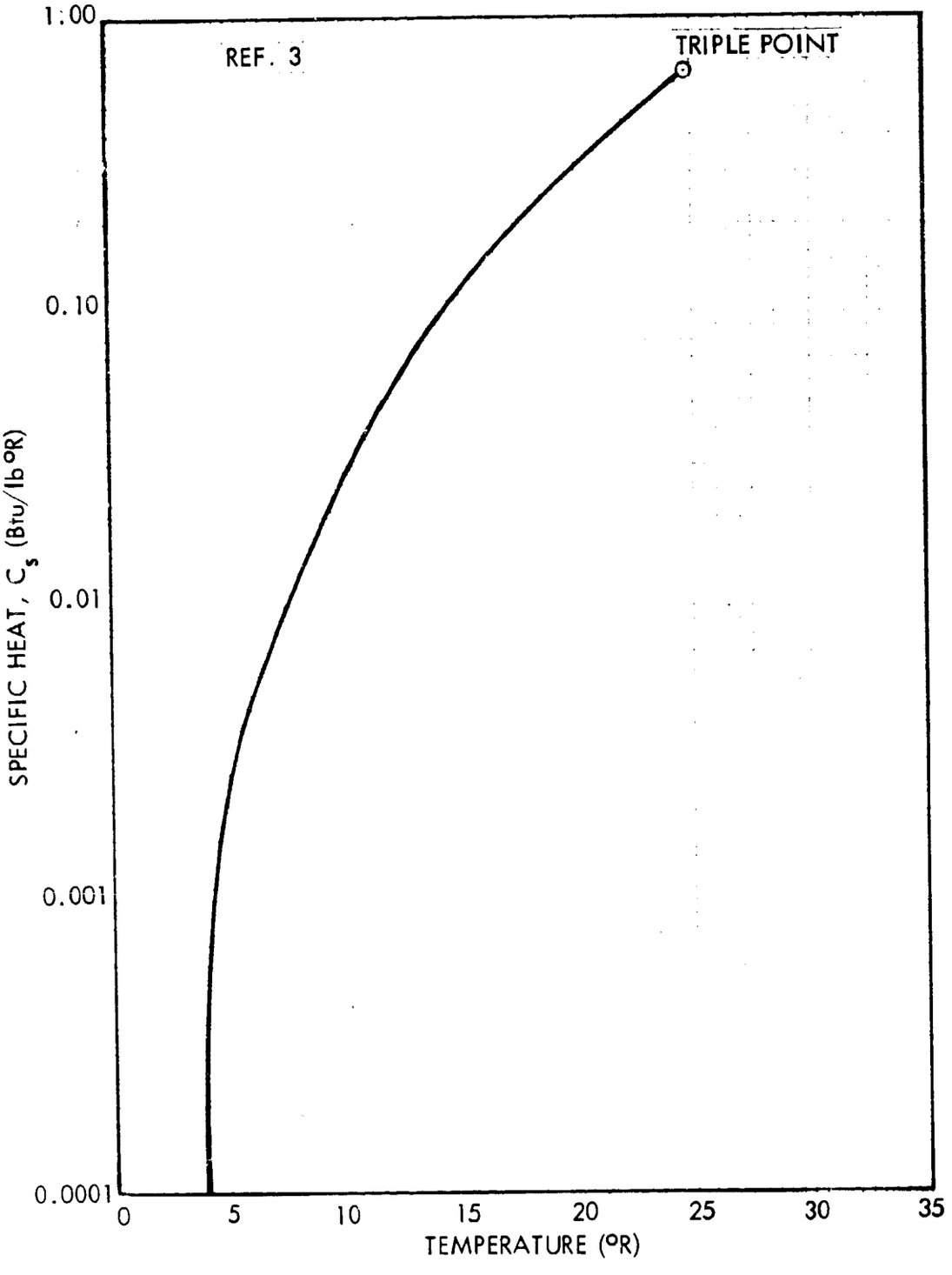

Fig. 2-13 Heat Capacity (C_s) of Saturated Solid Parahydrogen

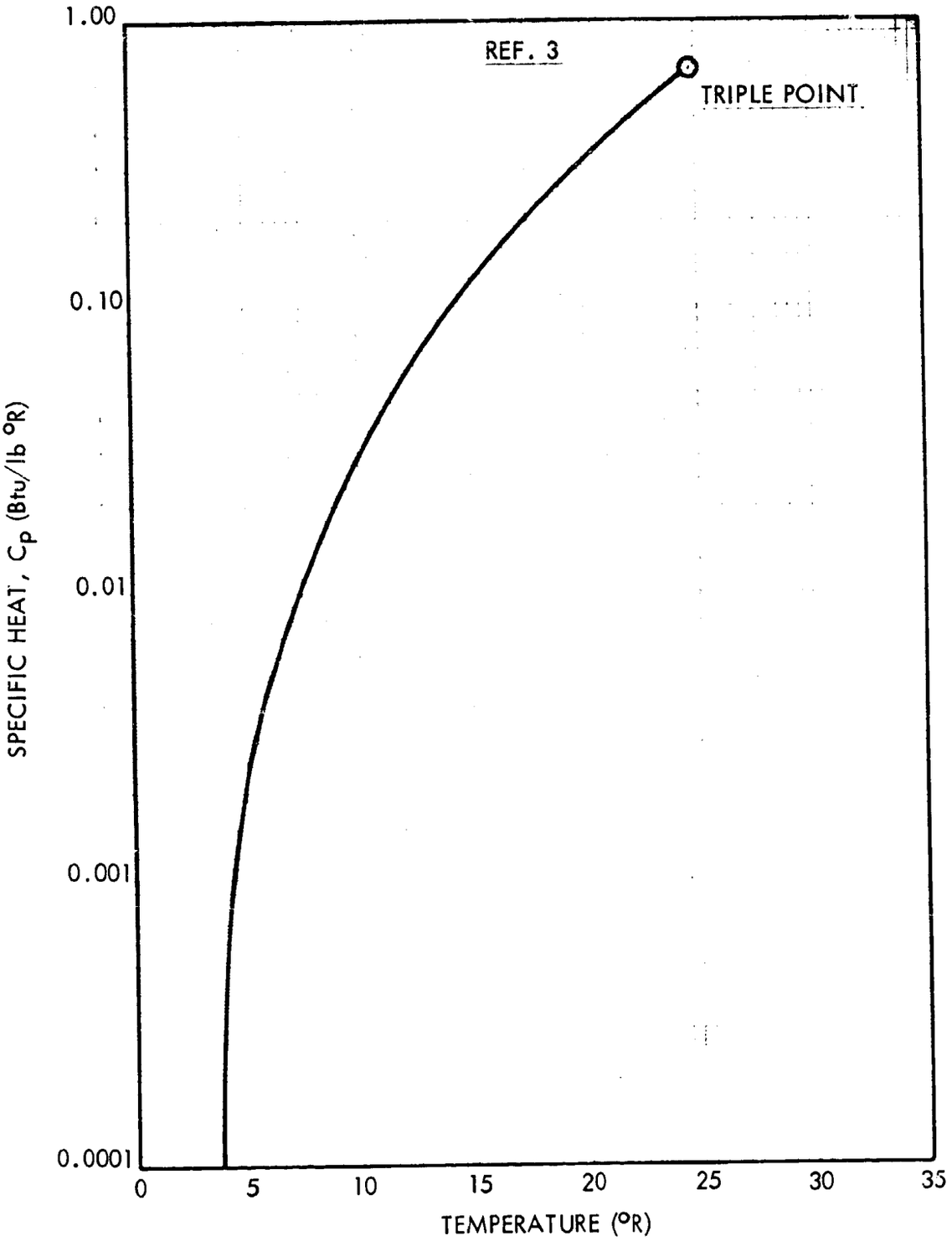

Fig. 2-14 Heat Capacity (C_p) of Saturated Solid Parahydrogen

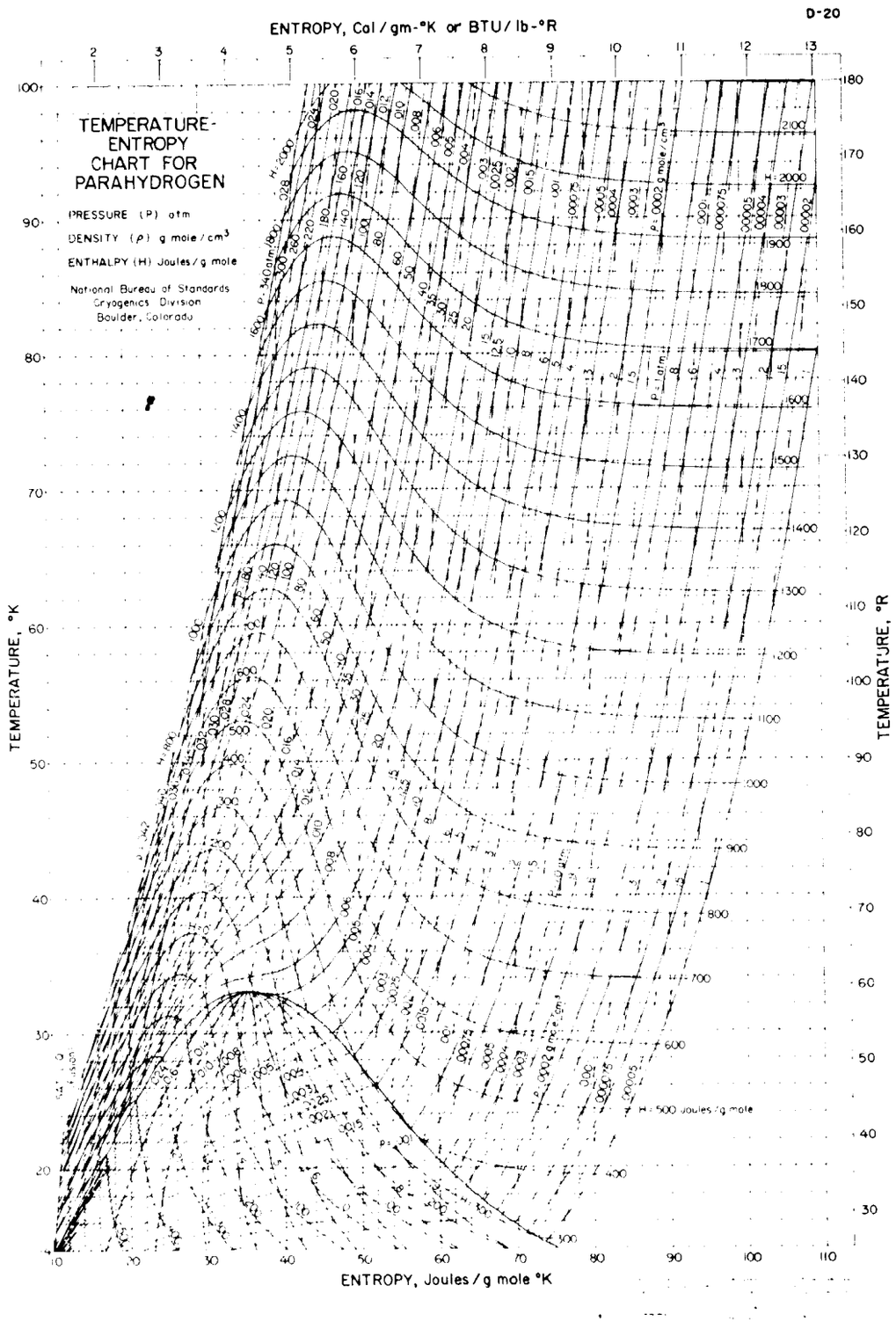

Fig. 2-15 Temperature-Entropy Diagram (English Units)
(From NBS File D5881, April 1965)

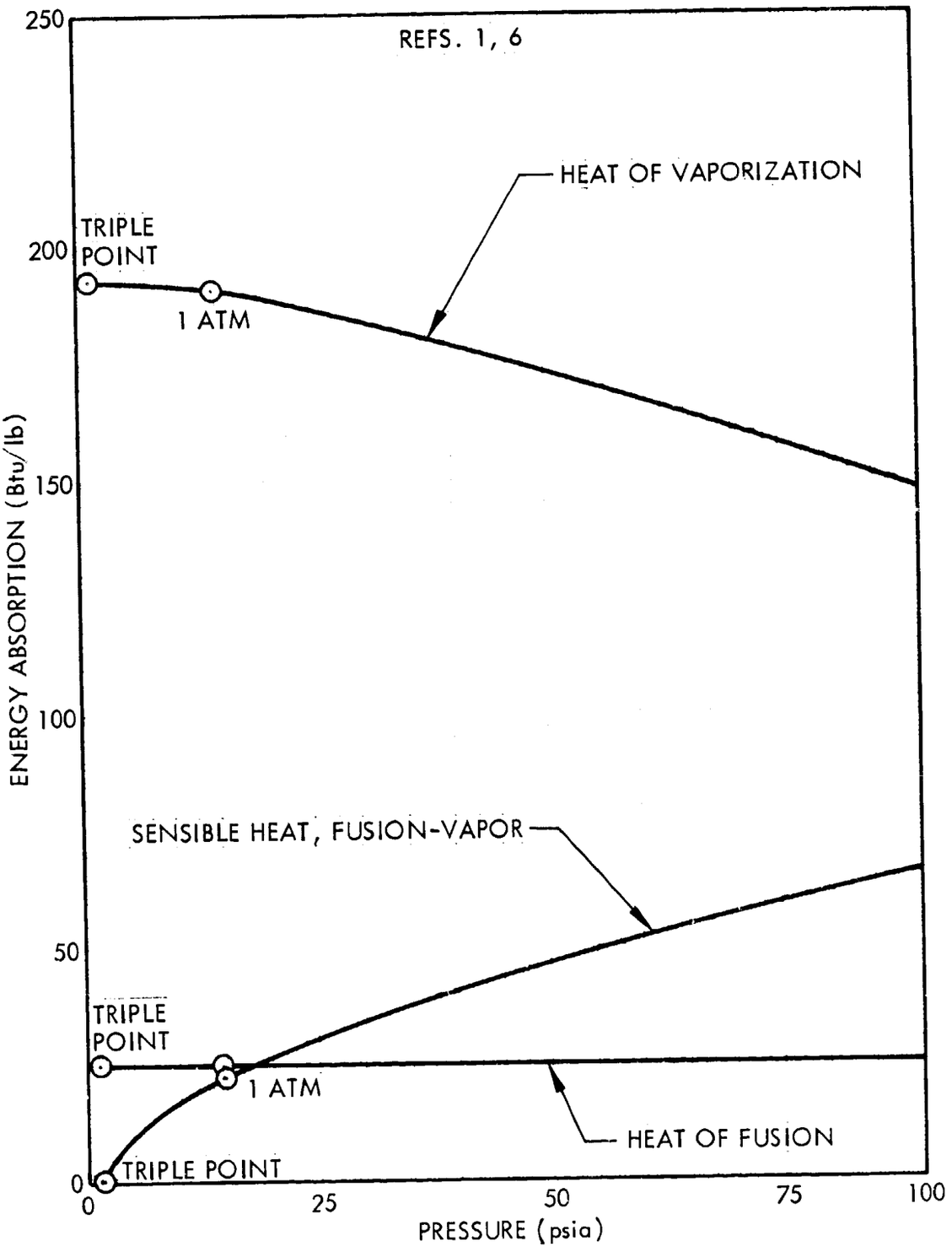

Fig. 2-16 Energy Absorption Capability of Saturated Parahydrogen

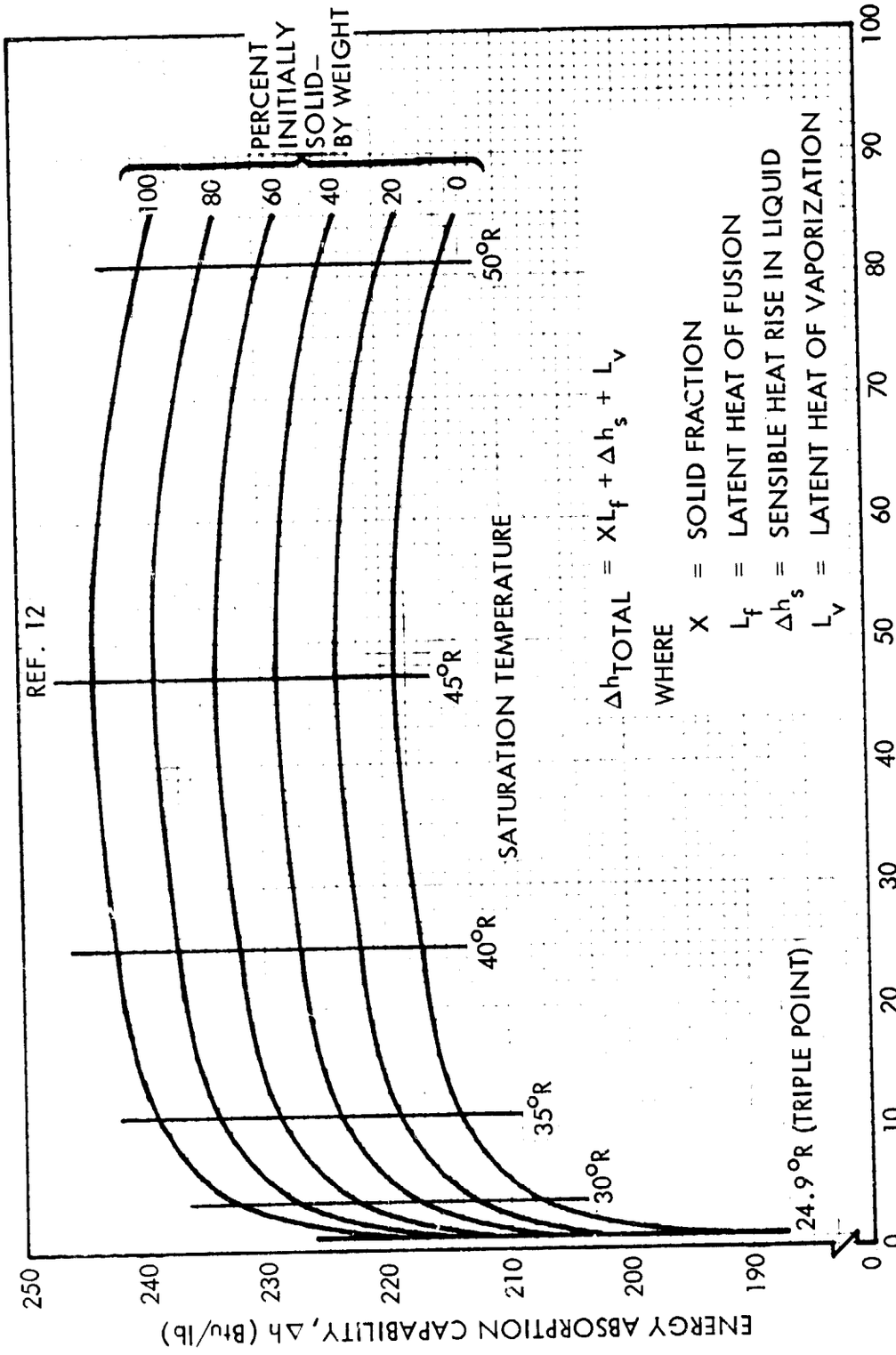

Fig. 2-17 Energy Absorption Capability of Liquid-Solid Mixtures of Parahydrogen

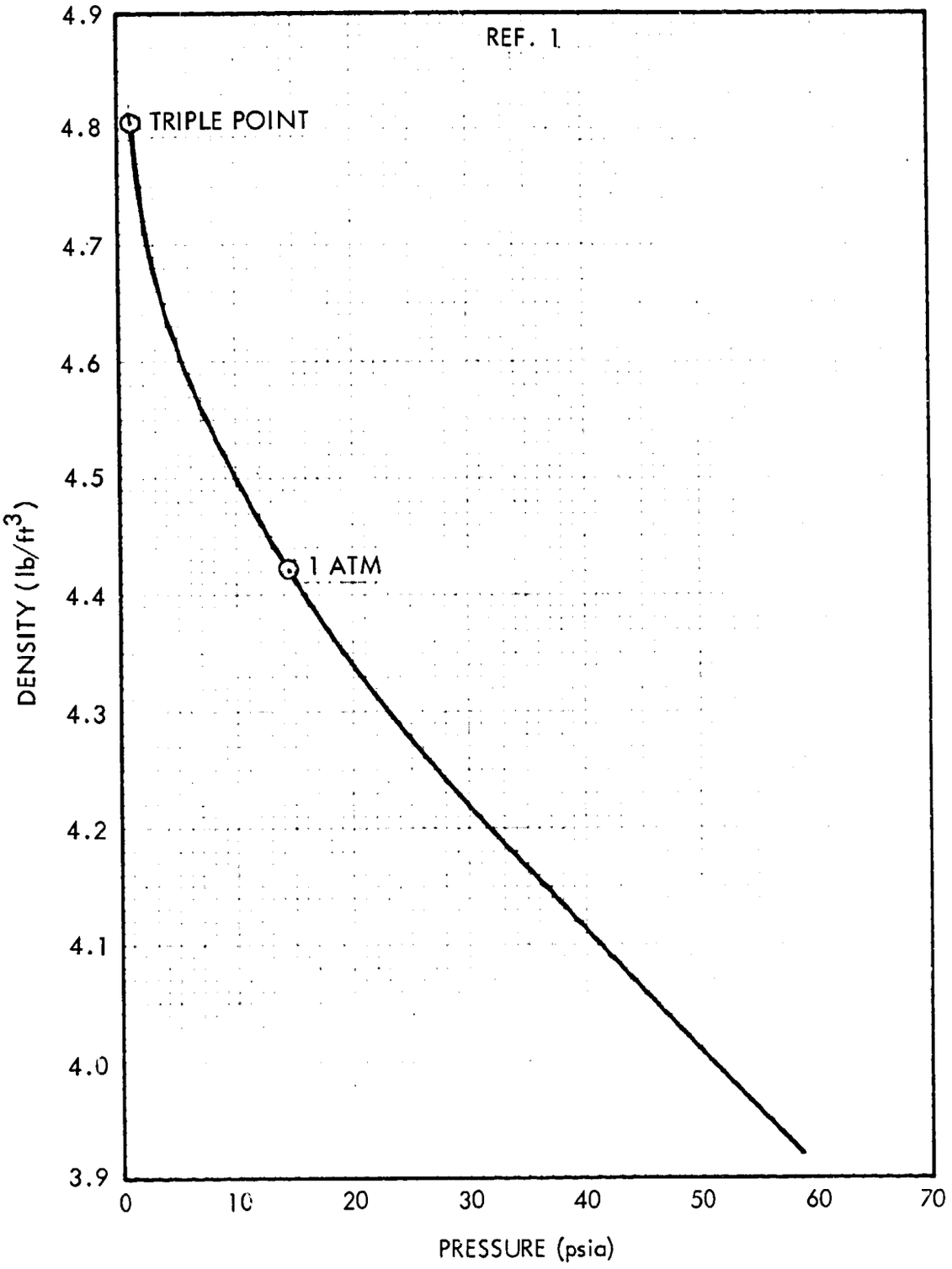

Fig. 2-18 Density of Saturated Parahydrogen Liquid

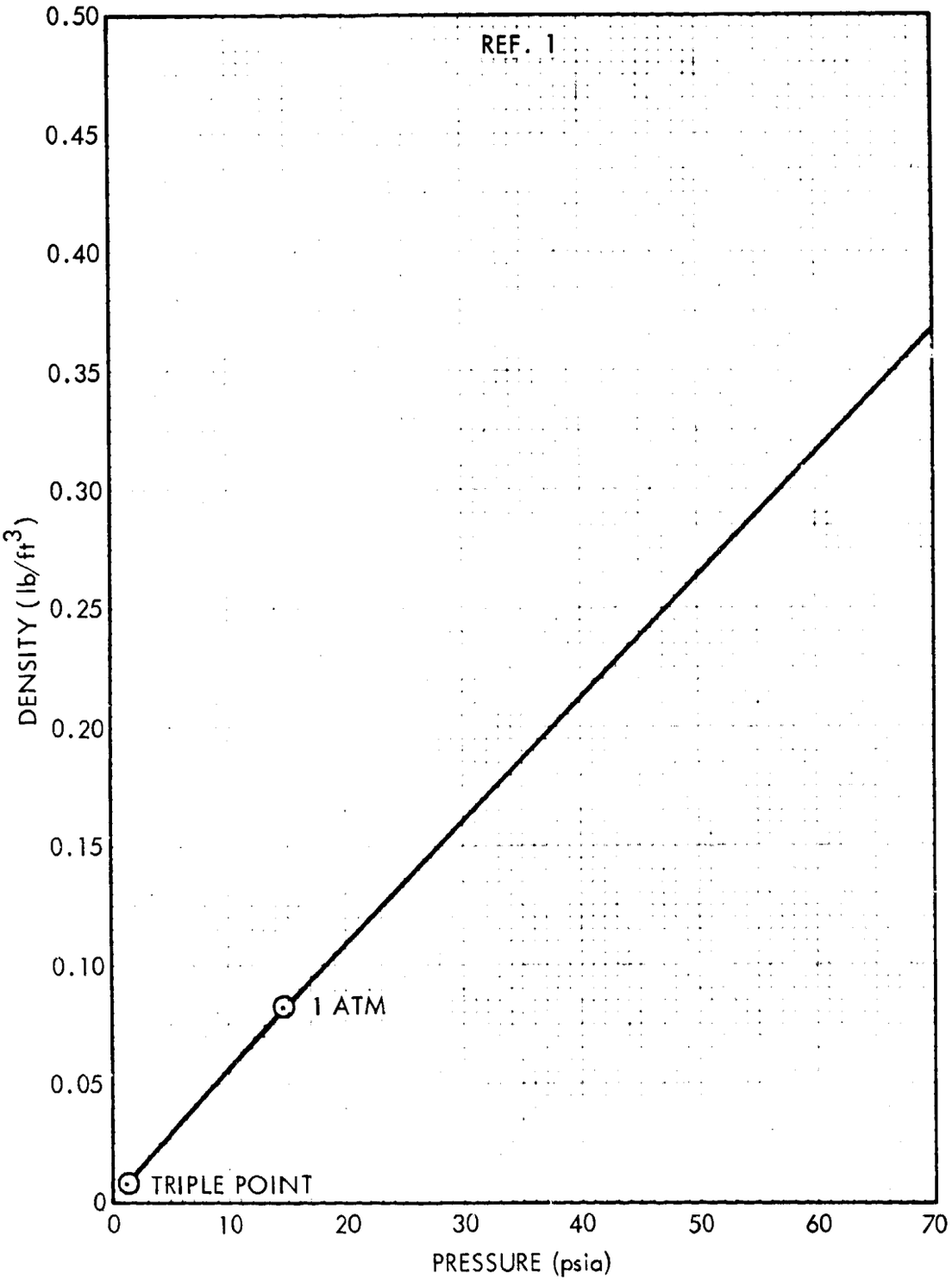

Fig. 2-19 Density of Saturated Parahydrogen Vapor

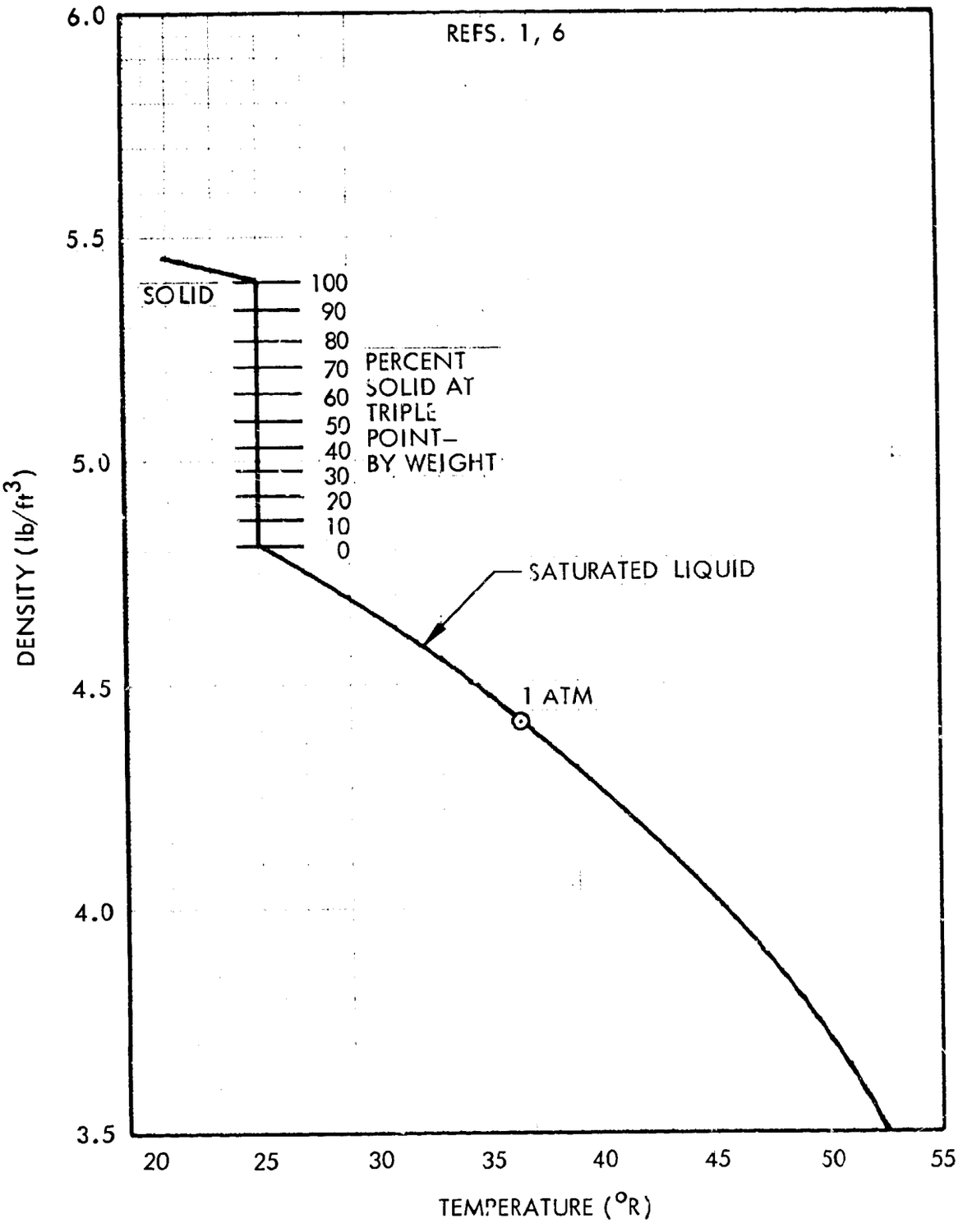

Fig. 2-20 Density of Liquid and Solid-Liquid Mixtures of Saturated Parahydrogen

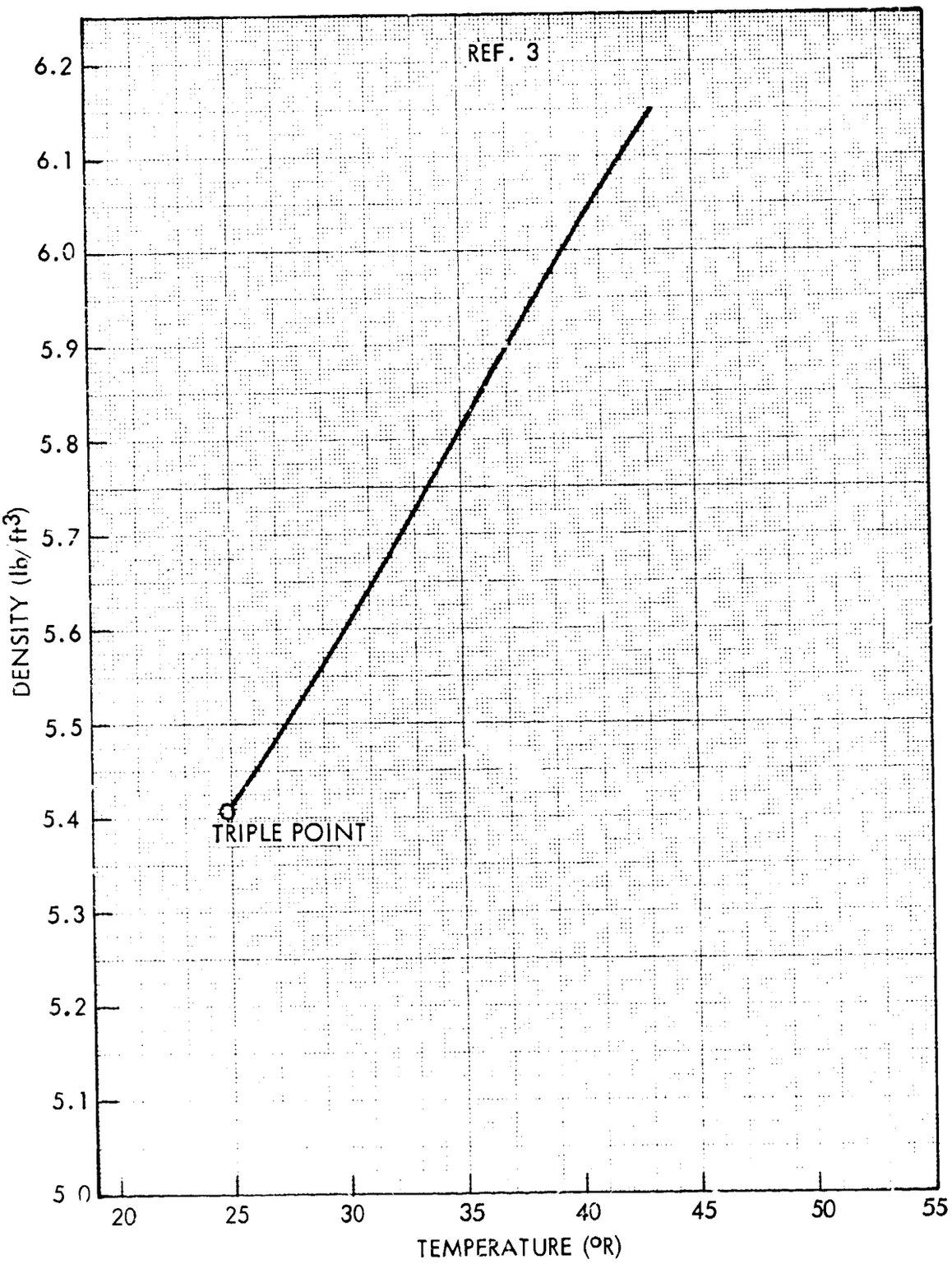

Fig. 2-21 Density of Solid Parahydrogen Along the Melting Line

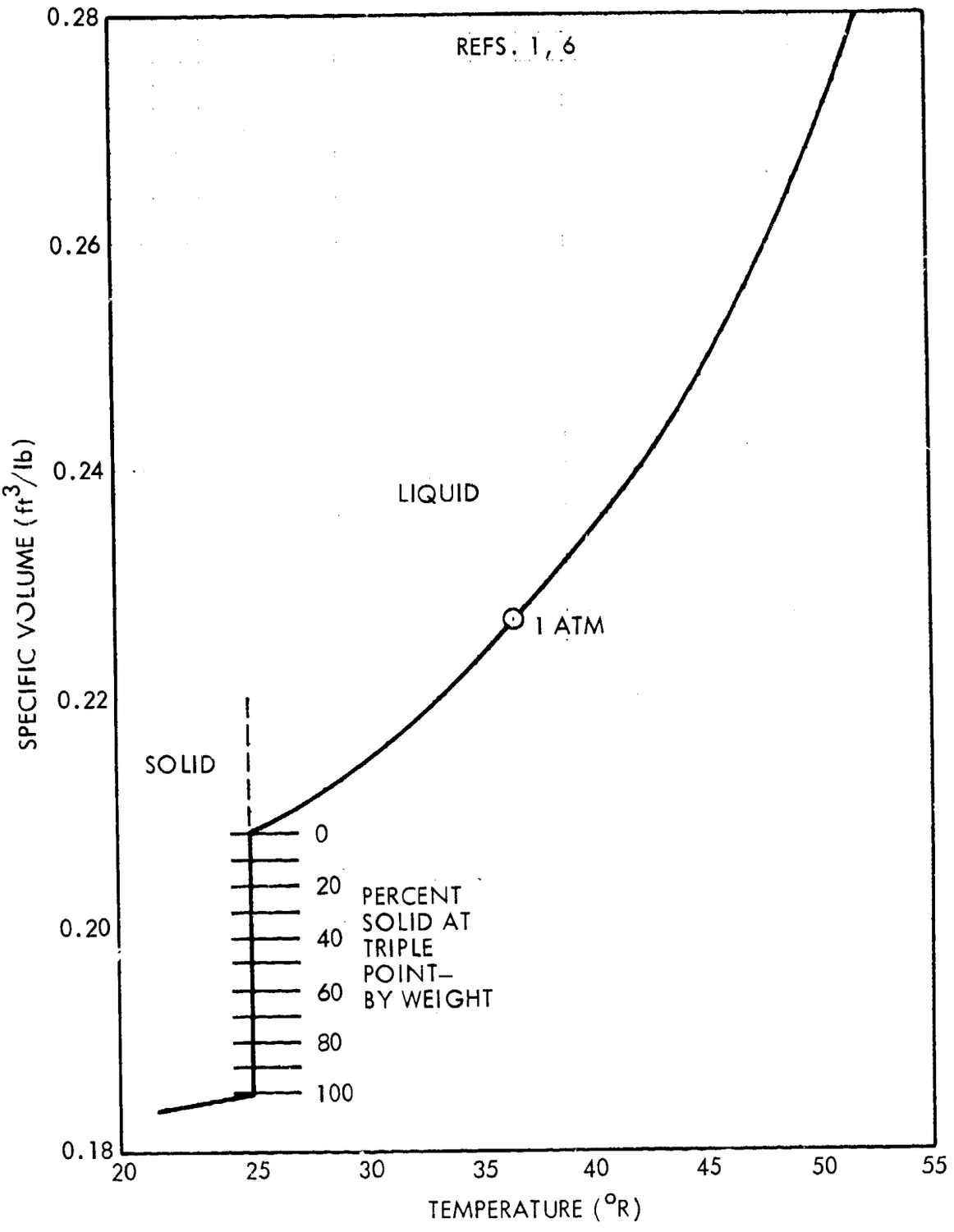

Fig. 2-22 Specific Volume of Liquid and Solid-Liquid Mixtures of Saturated Parahydrogen

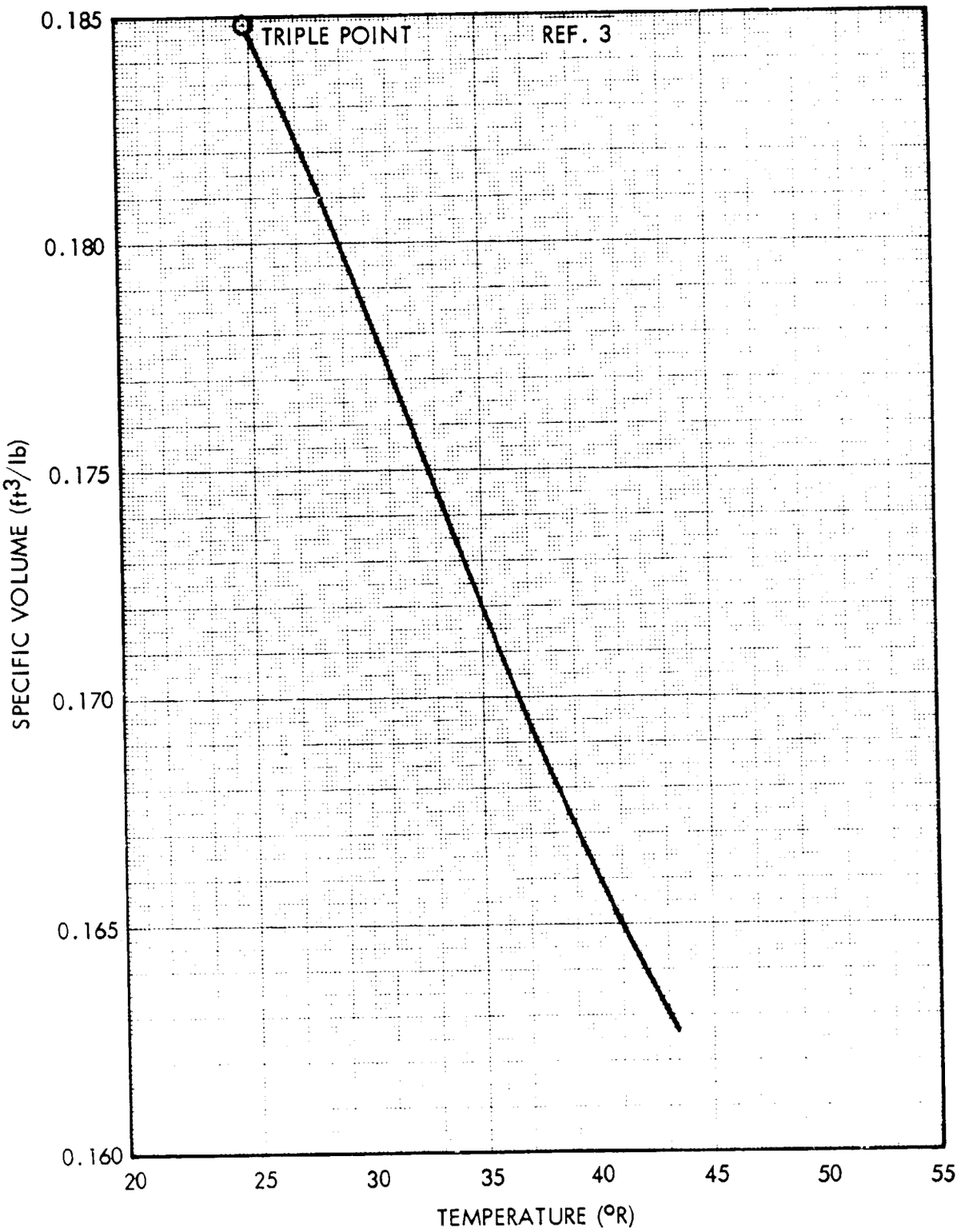

Fig. 2-23 Specific Volume of Solid Parahydrogen Along the Melting Line

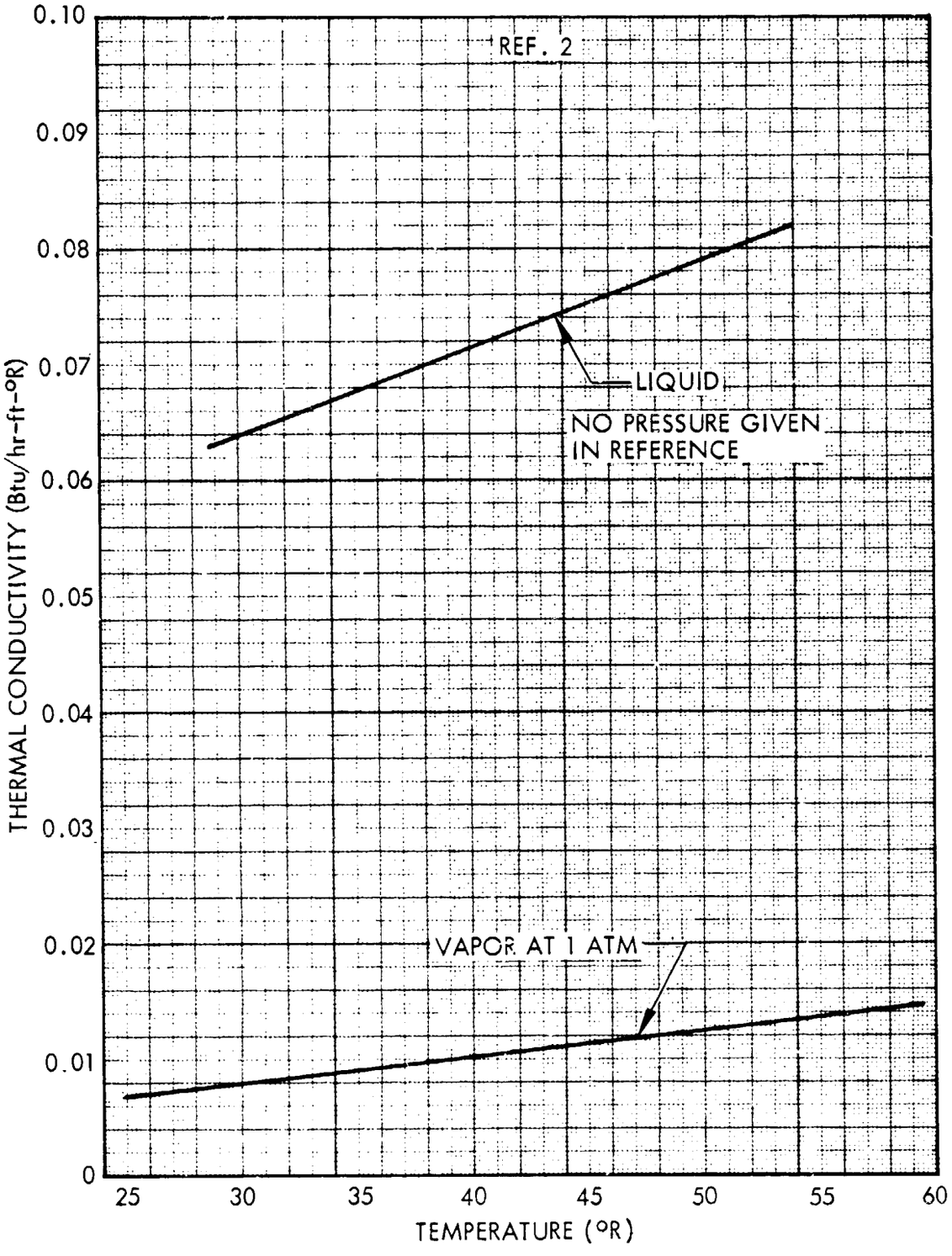

Fig. 2-24 Thermal Conductivity of Parahydrogen Liquid and Vapor

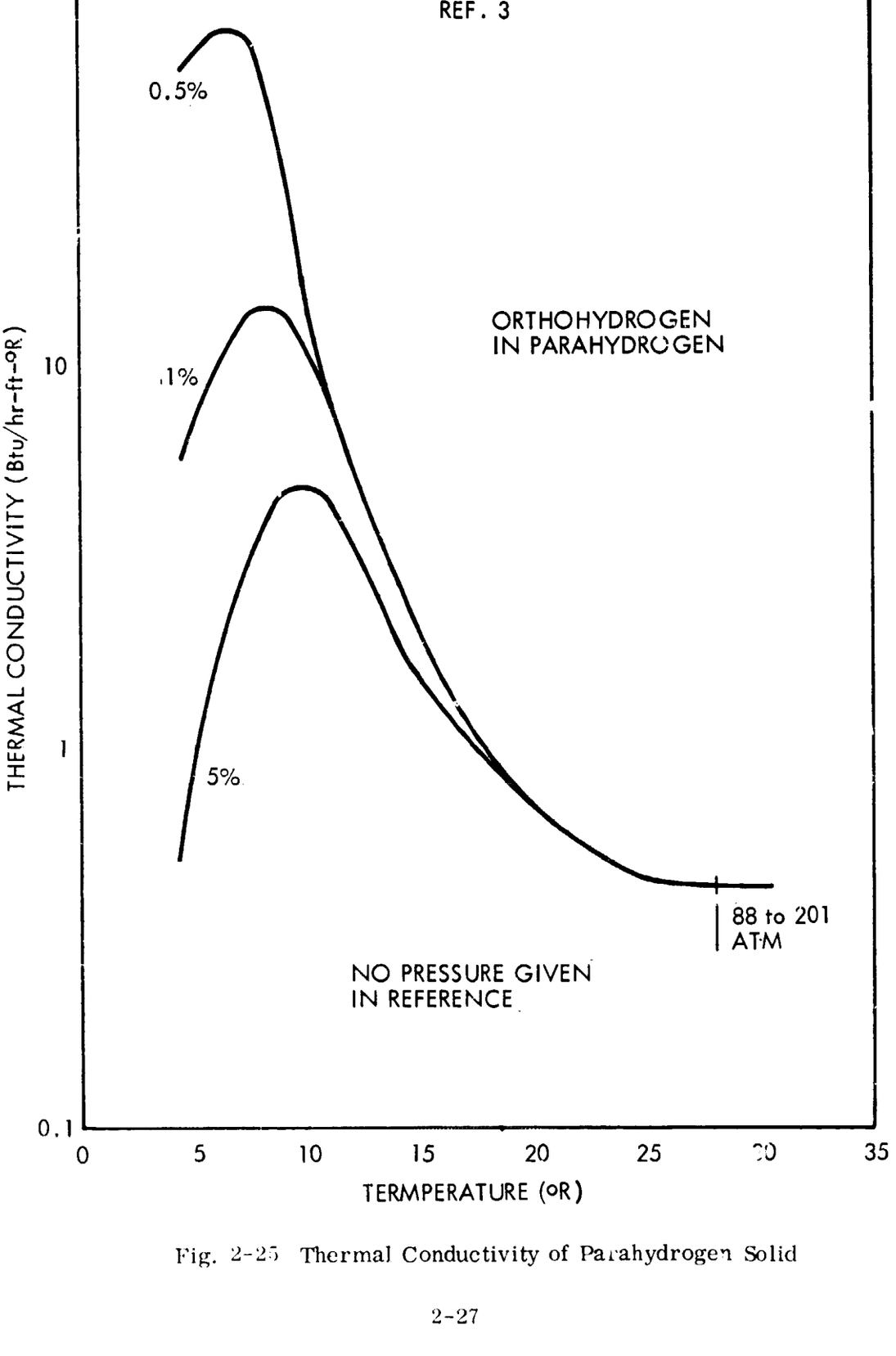

Fig. 2-25 Thermal Conductivity of Parahydrogen Solid

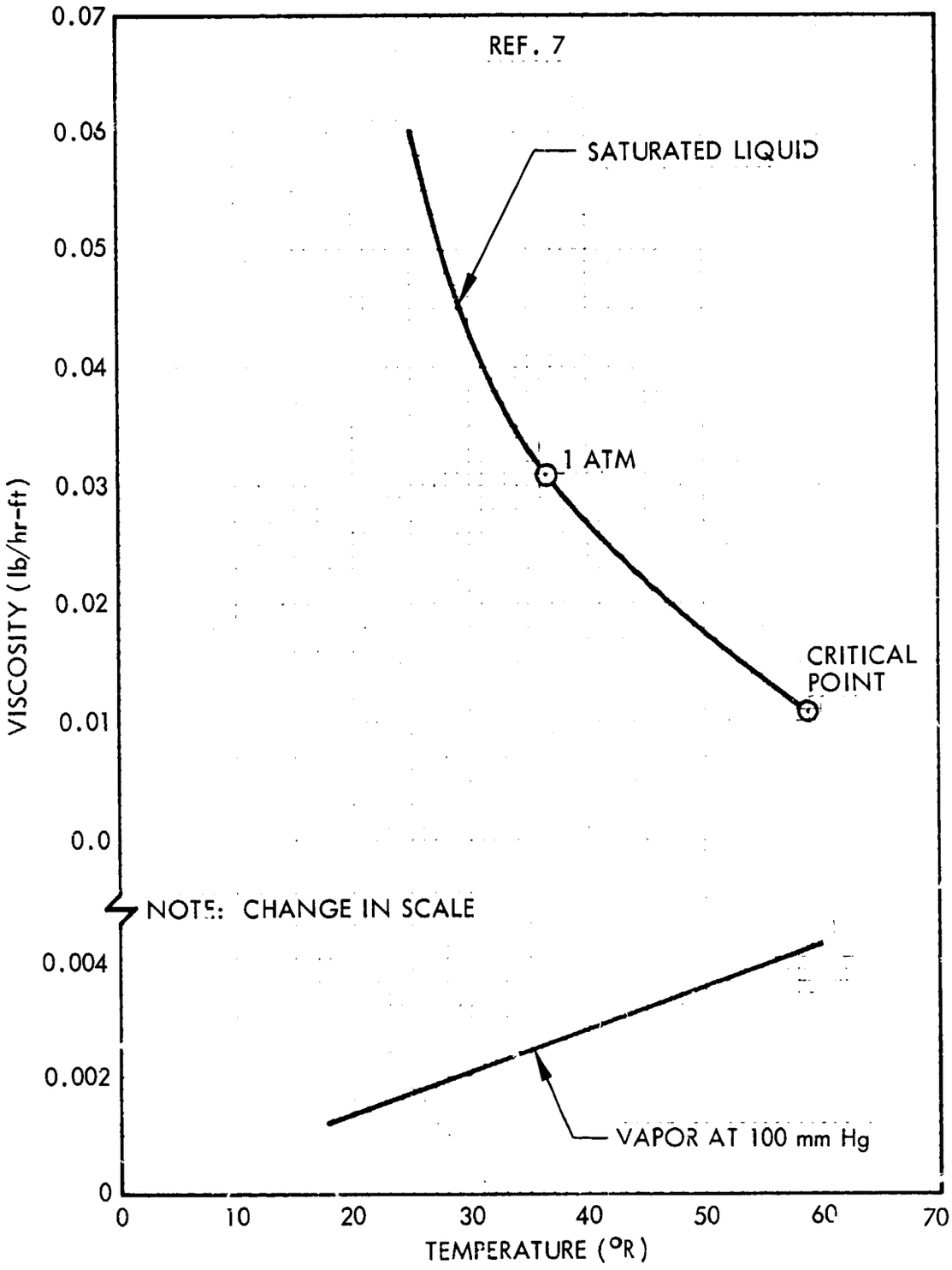

Fig. 2-26 Viscosity of Parahydrogen

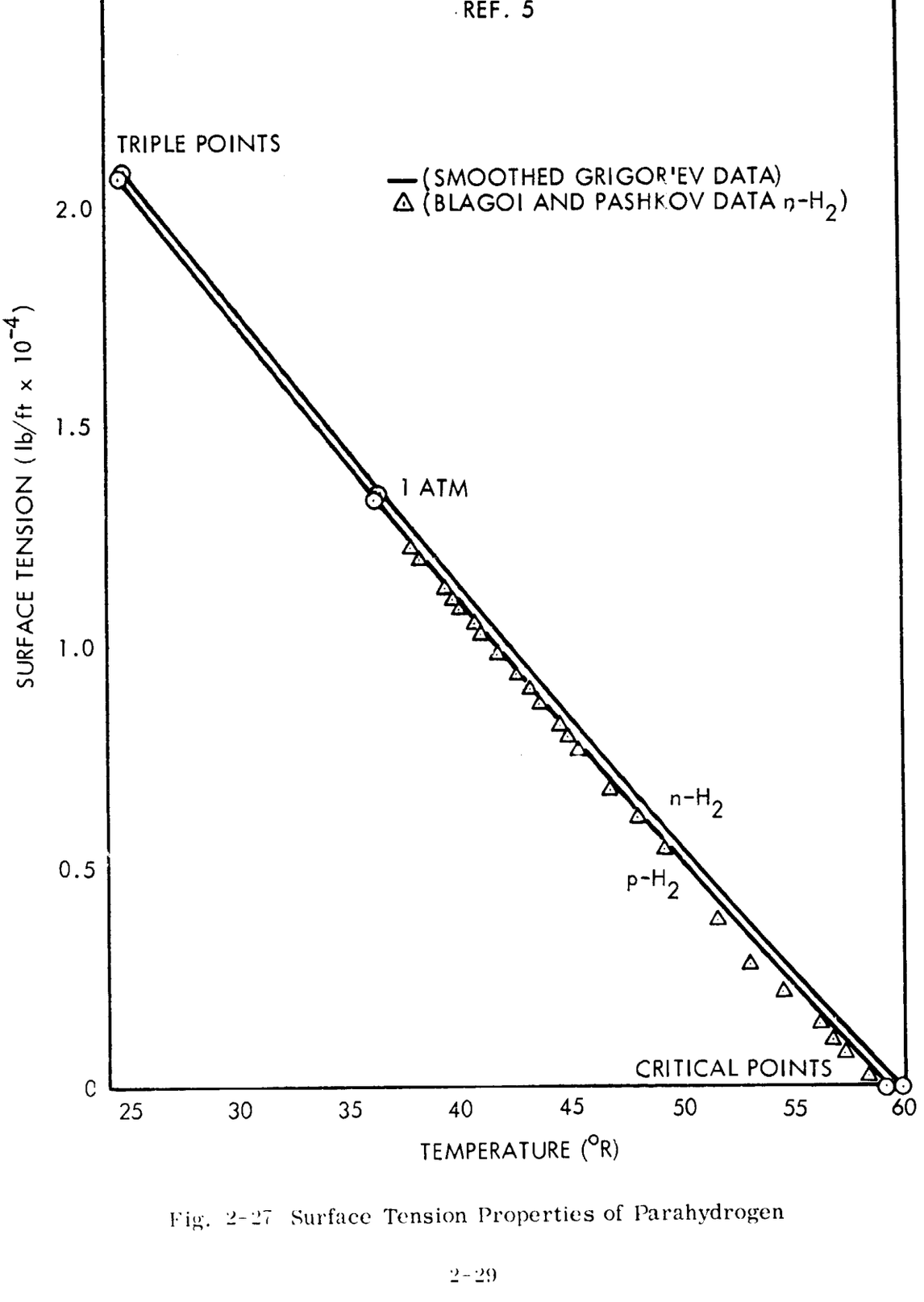

Fig. 2-27 Surface Tension Properties of Parahydrogen

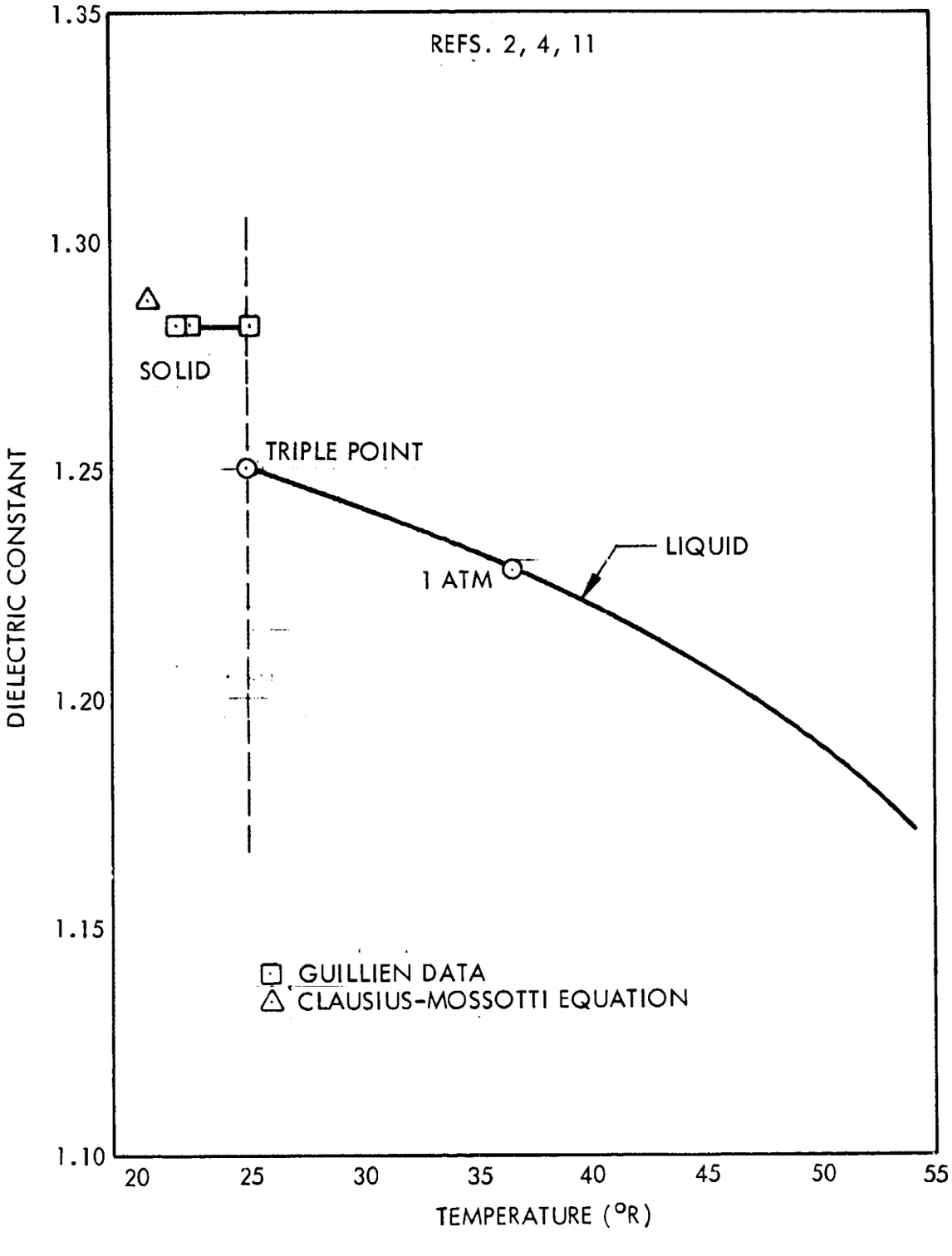

Fig. 2-28 Dielectric Constant of Parahydrogen Solid and Liquid

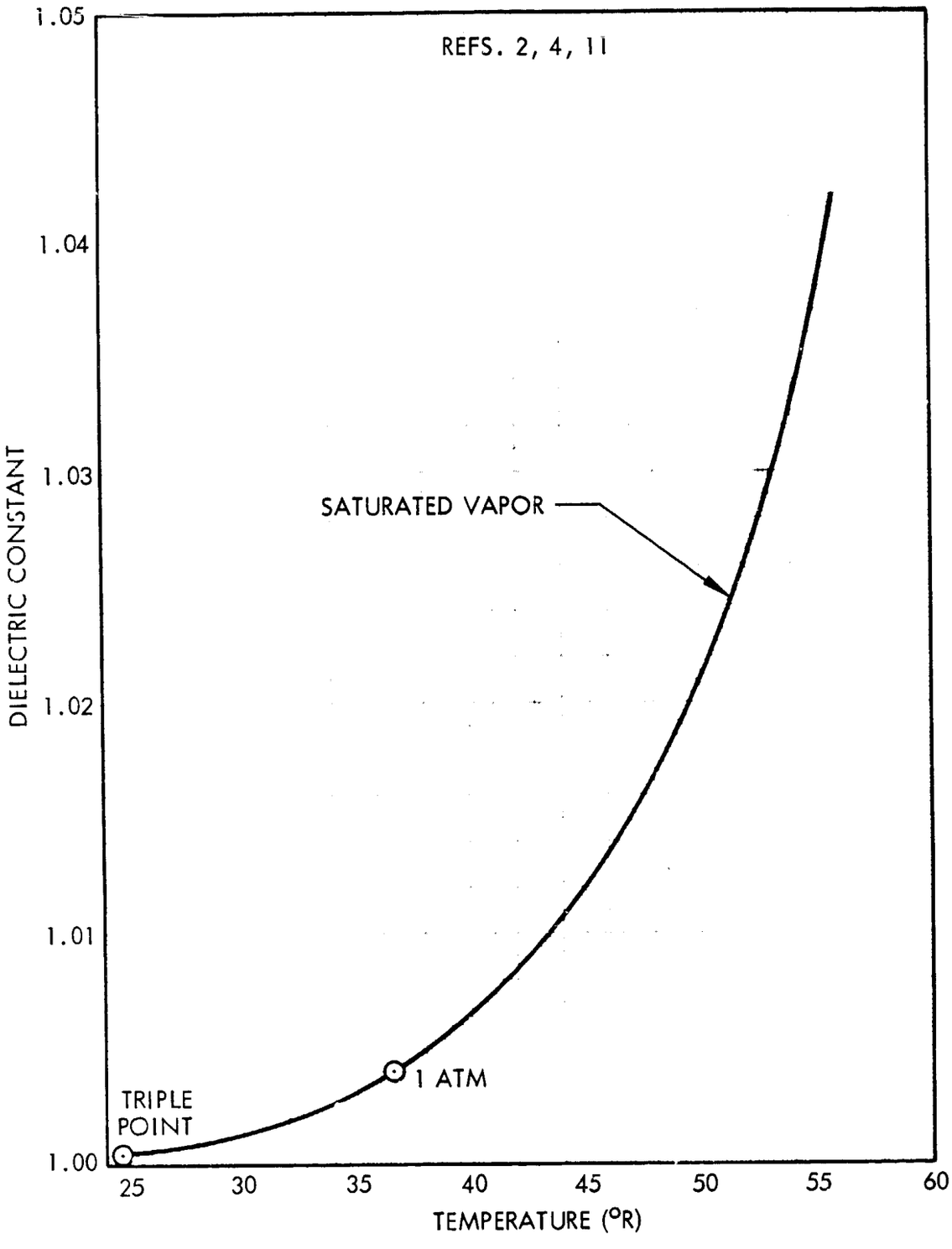

Fig. 2-29 Dielectric Constant of Parahydrogen Vapor

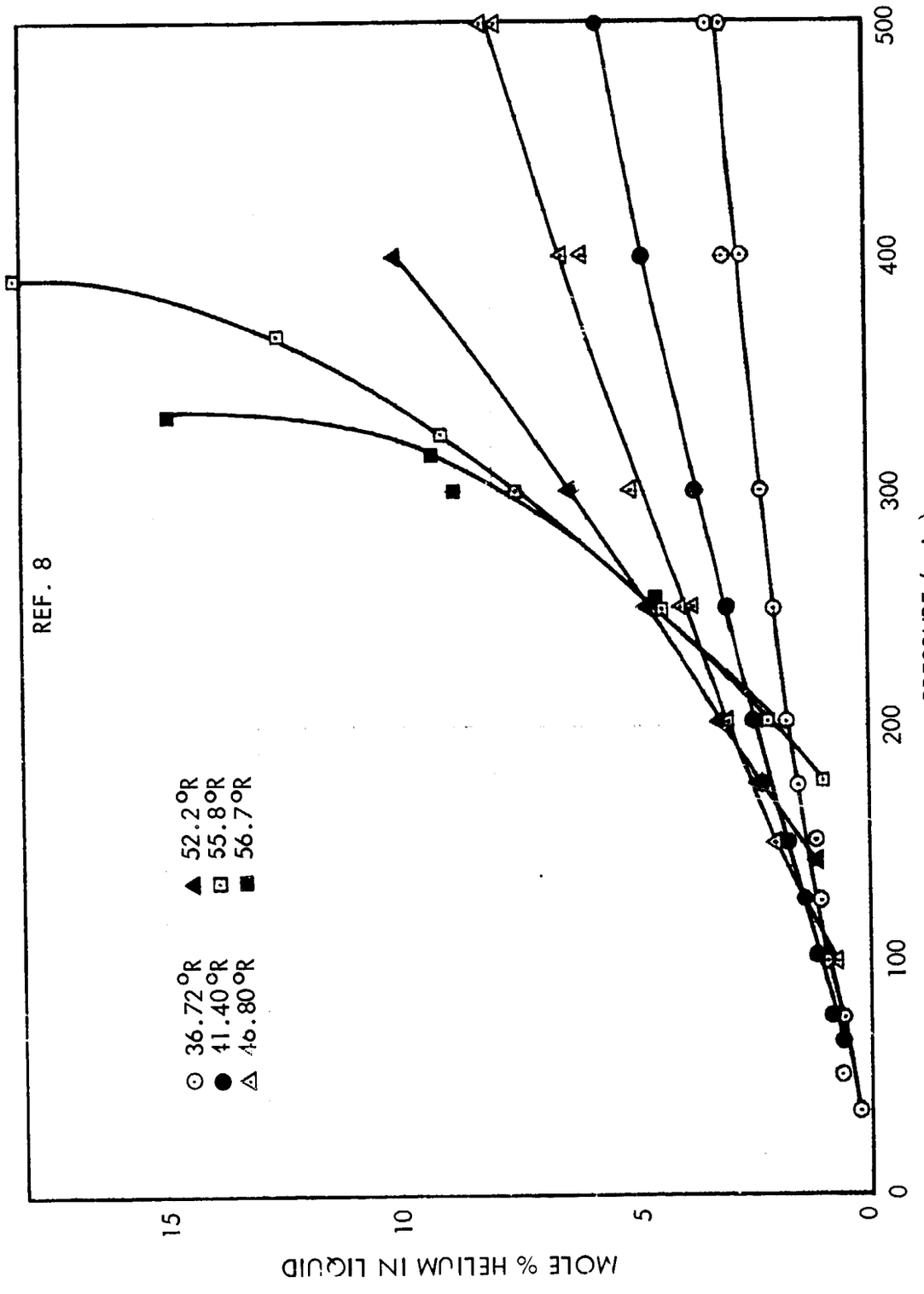

Fig. 2-30 Solubility of Helium Vapor in Equilibrium Hydrogen Liquid

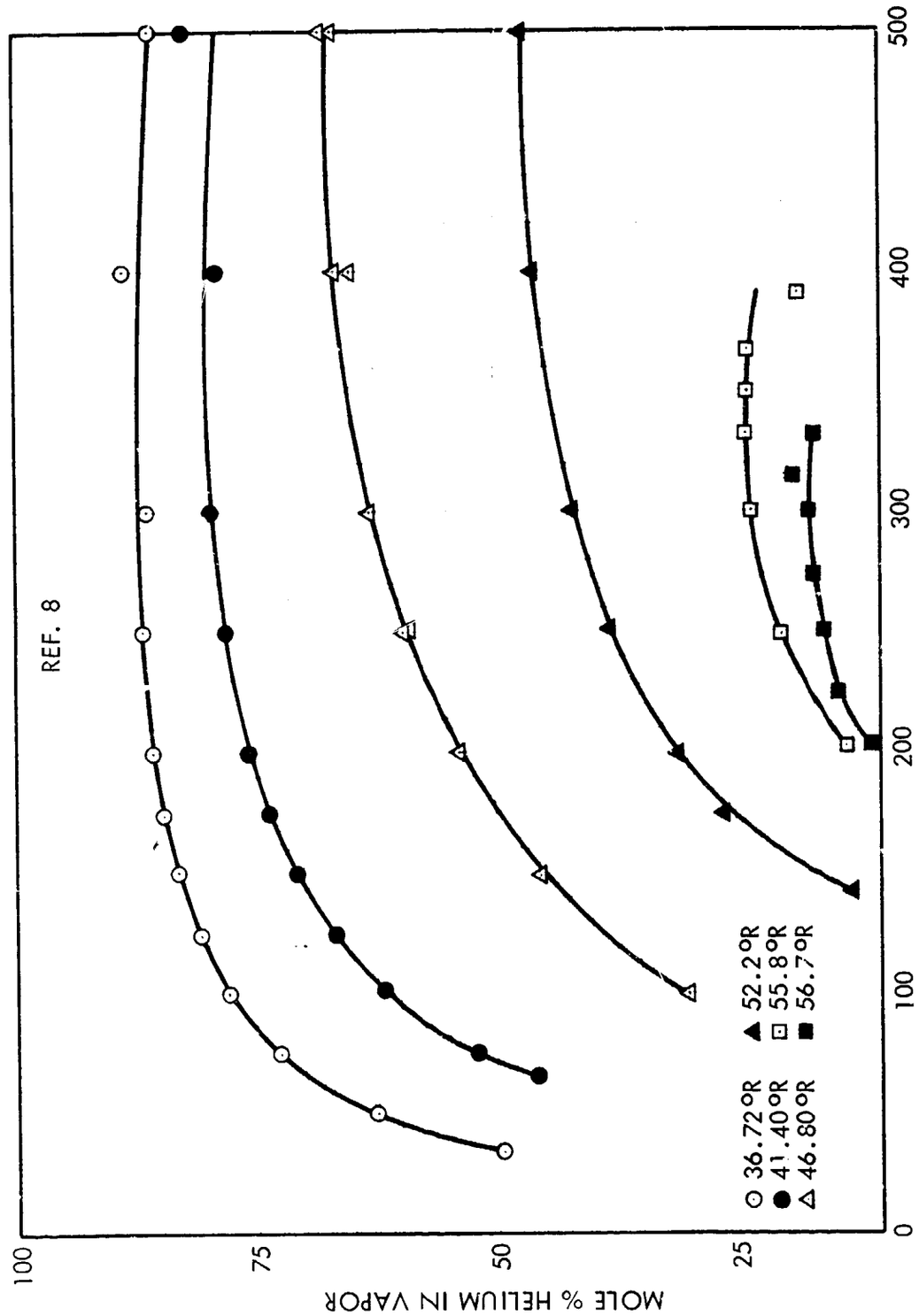

Fig. 2-31 Isothermal Pressure – Composition Diagram for 36.7°R Equilibrium Hydrogen Vapor – Helium Vapor System

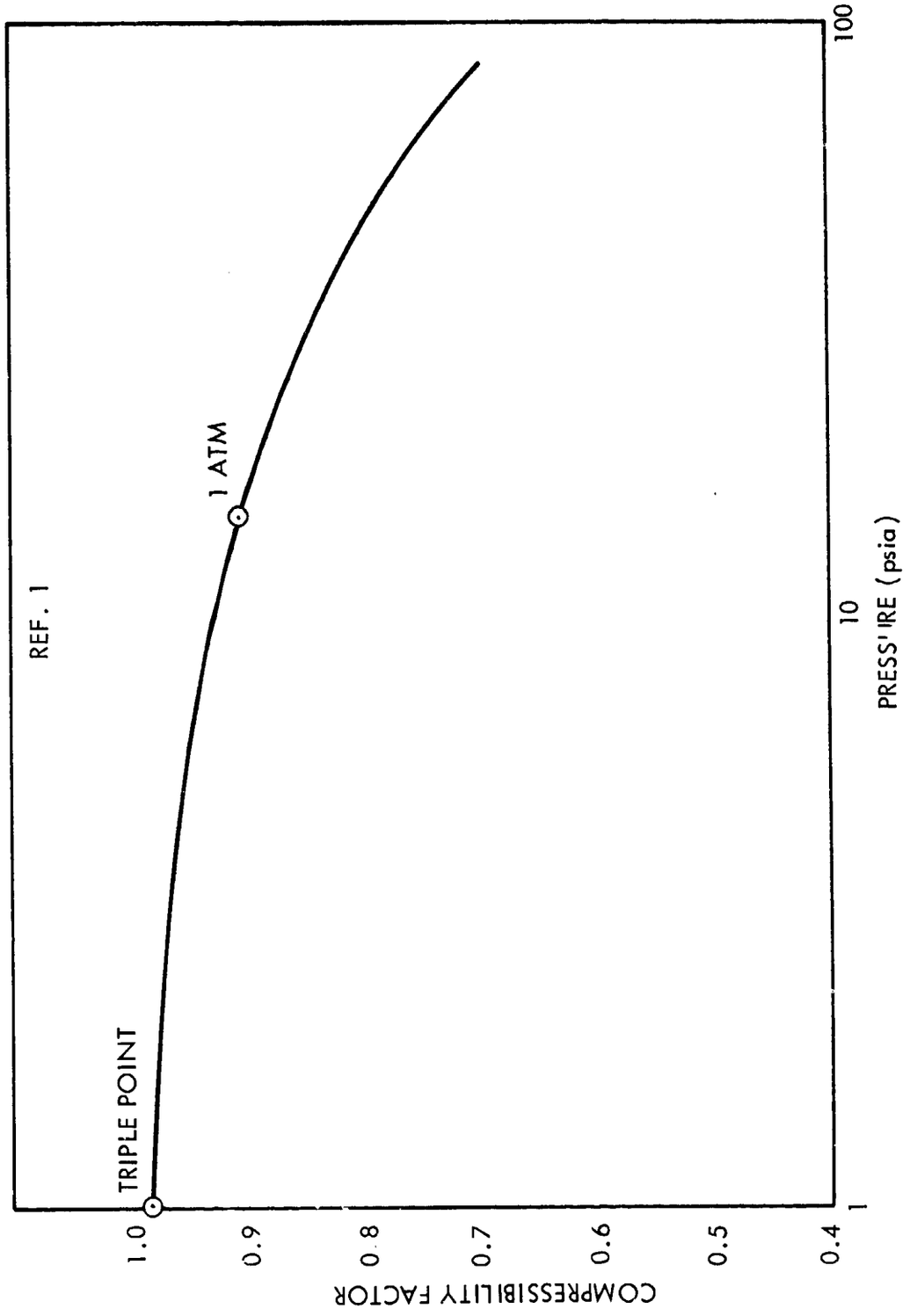

Fig. 2-32 Compressibility of Saturated Parahydrogen Vapor

Section 3
PHYSICAL-THERMAL PROPERTIES OF HYDROGEN IN INTERNATIONAL UNITS

Physical and thermal property data for hydrogen in the regions between the triple-point and the critical-point are presented in the International system of units in the following table and illustrations.

Table 3-1

REFERENCE POINT PROPERTIES
(International Units)

Physical Property	Triple Point	One Atmosphere	Critical Point
Parahydrogen, Percent	99.789 (a)	99.789(b)	99.55 (c)
Temperature, °K	13.803	20.268	32.976
Pressure, N/cm^2	0.704	10.133	129.281
Enthaply, joules/gm			
Saturated Vapor	140.297	189.323	38.1
Saturated Liquid	-308.921	-256.234	38.5
Density, kg/m^3			
Saturated Liquid	77.024	70.889	31.447
50% Liquid—50% Slush	81.54	(d)	(d)
100% Solid	86.636	(d)	(d)
Saturated Vapor	0.128	1.3457	31.44"
Viscosity, gm/cm sec			
Vapor at 10 cm Hg	(d)	(d)	(d)
Saturated Liquid	(e)	$(131 \times 10^{-6}$(c)	(43.9×10^{-6}) (c)
Surface Tension, N/cm	2.990×10^{-5}	1.930×10^{-5}	0.0
Dielectric Constant			
Saturated Vapor	1.0004	1.0040	1.09733
Saturated Liquid	1.2503	1.2285	1.1267(c)
Solid	(1.2505)(c)	(d)	(d)
Compressibility Factor			
Saturated Vapor	0.9838(f)	0.9060(f)	0.3024(f)

(a) This value is suitable due to the time required to reach equilibrium.
(b) At temperatures 0.6% off one atmosphere saturated temperature.
(c) Either read from plot or interpolated.
(d) Calculated using referenced properties.
(e) Not applicable.
(f) No data given or uncertain conditions.

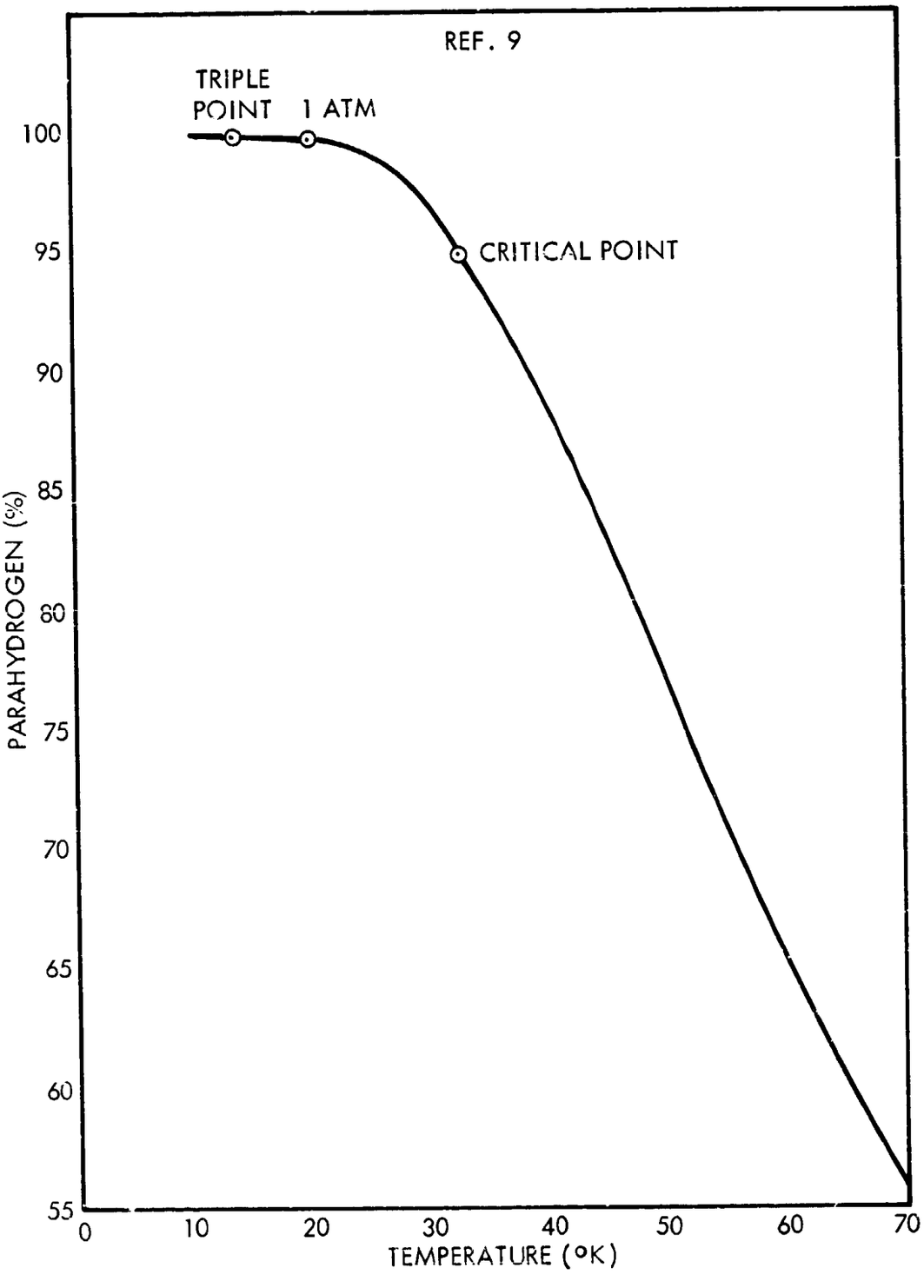

Fig. 3-1 Parahydrogen Composition of Ortho-para Mixture at Equilibrium

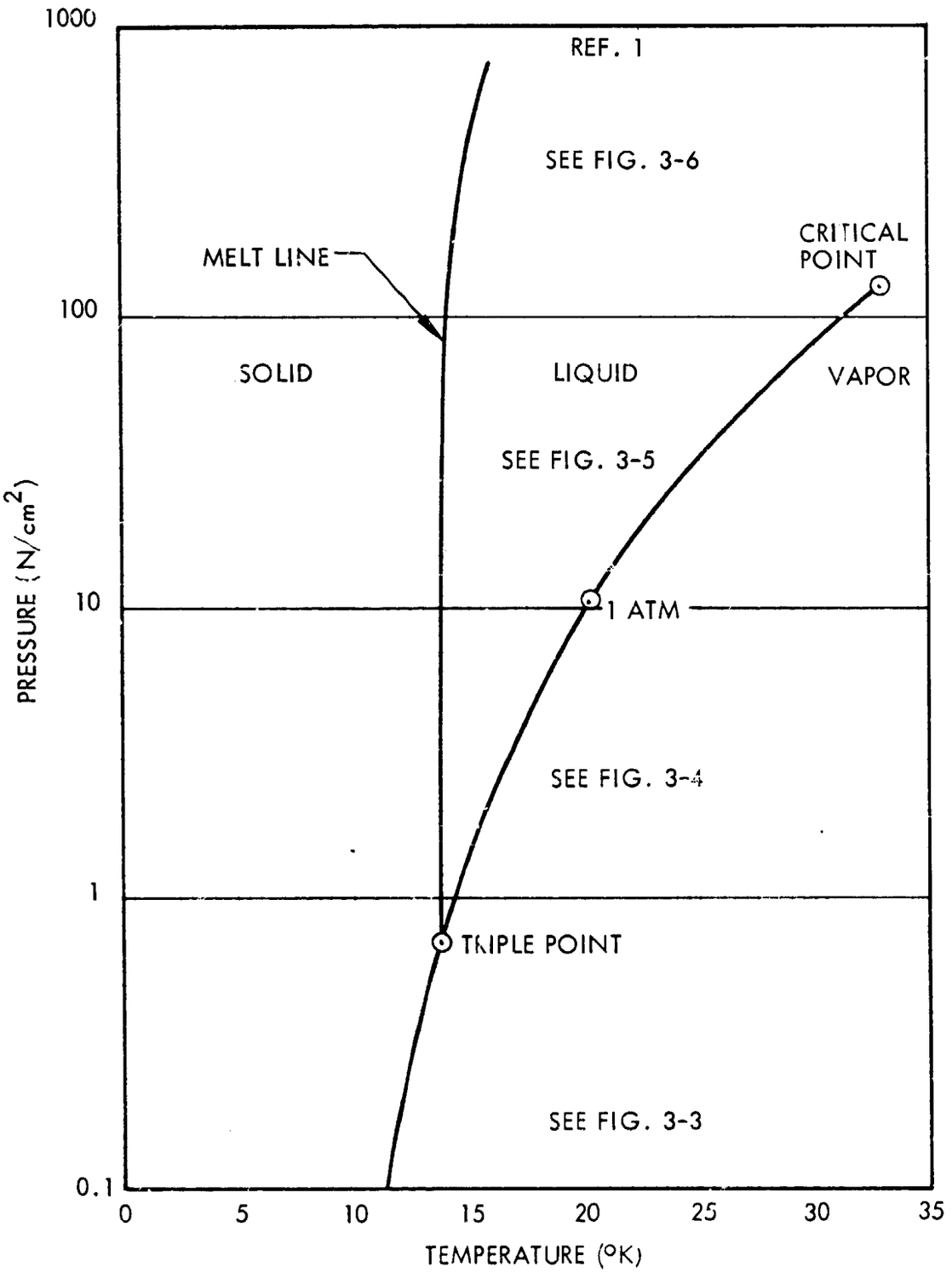

Fig. 3-2 Parahydrogen Pressure-Temperature Phase Diagram

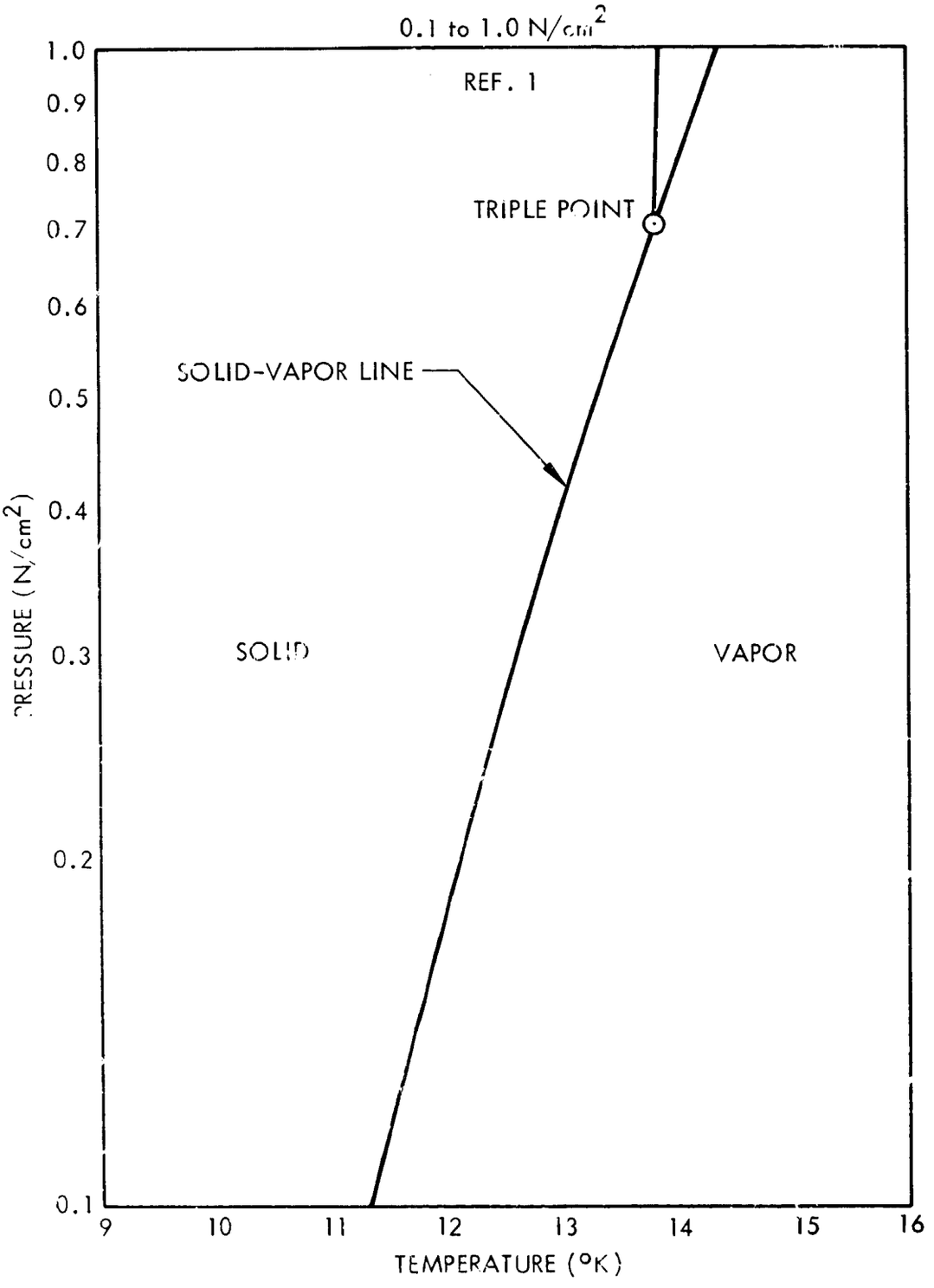

Fig. 3-3 Parahydrogen Pressure-Temperature Phase Diagram (0.1 to 1.0 N/cm^2)

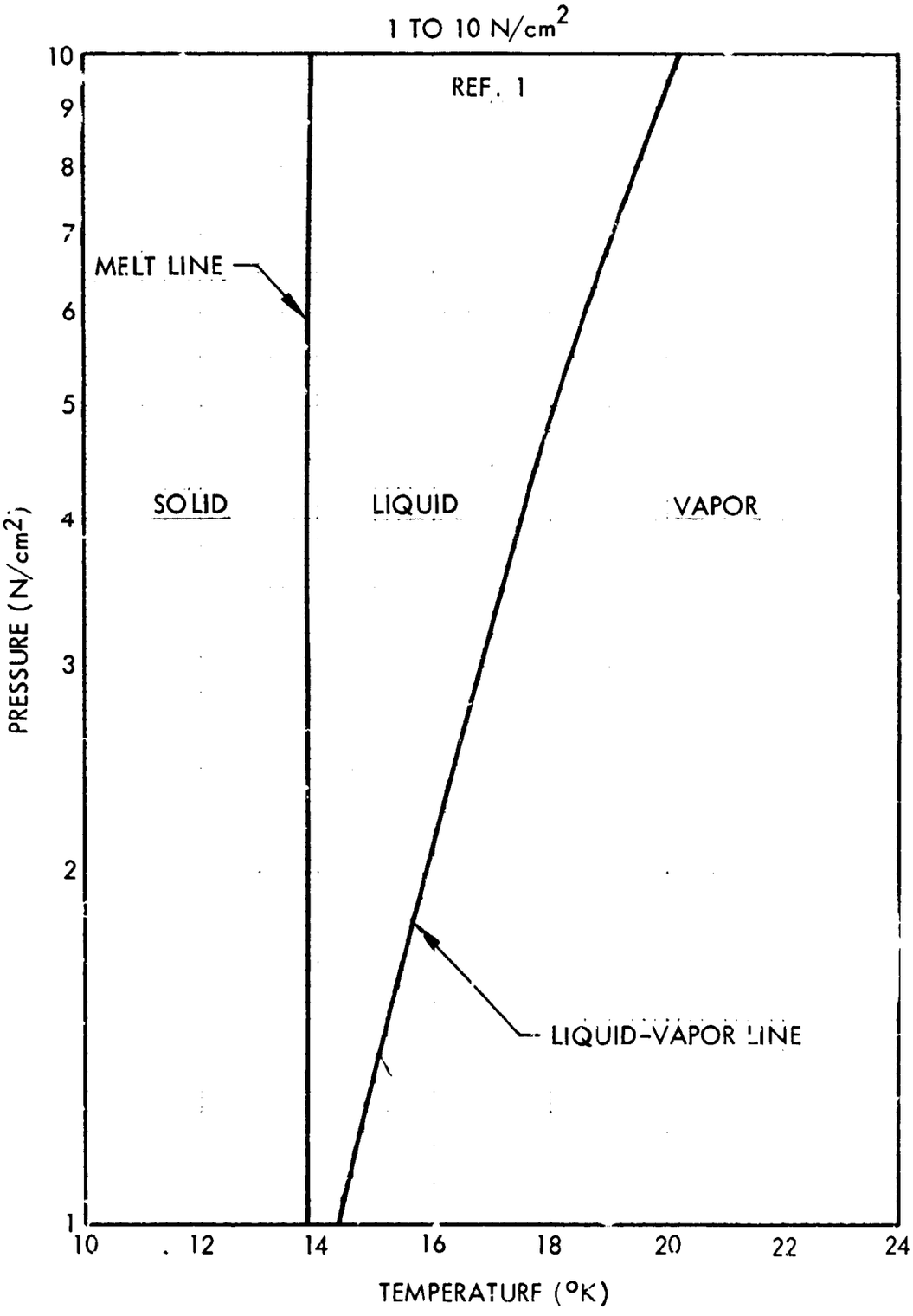

Fig. 3-4 Parahydrogen Pressure-Temperature Phase Diagram (1.0 to 10.0 N/cm^2)

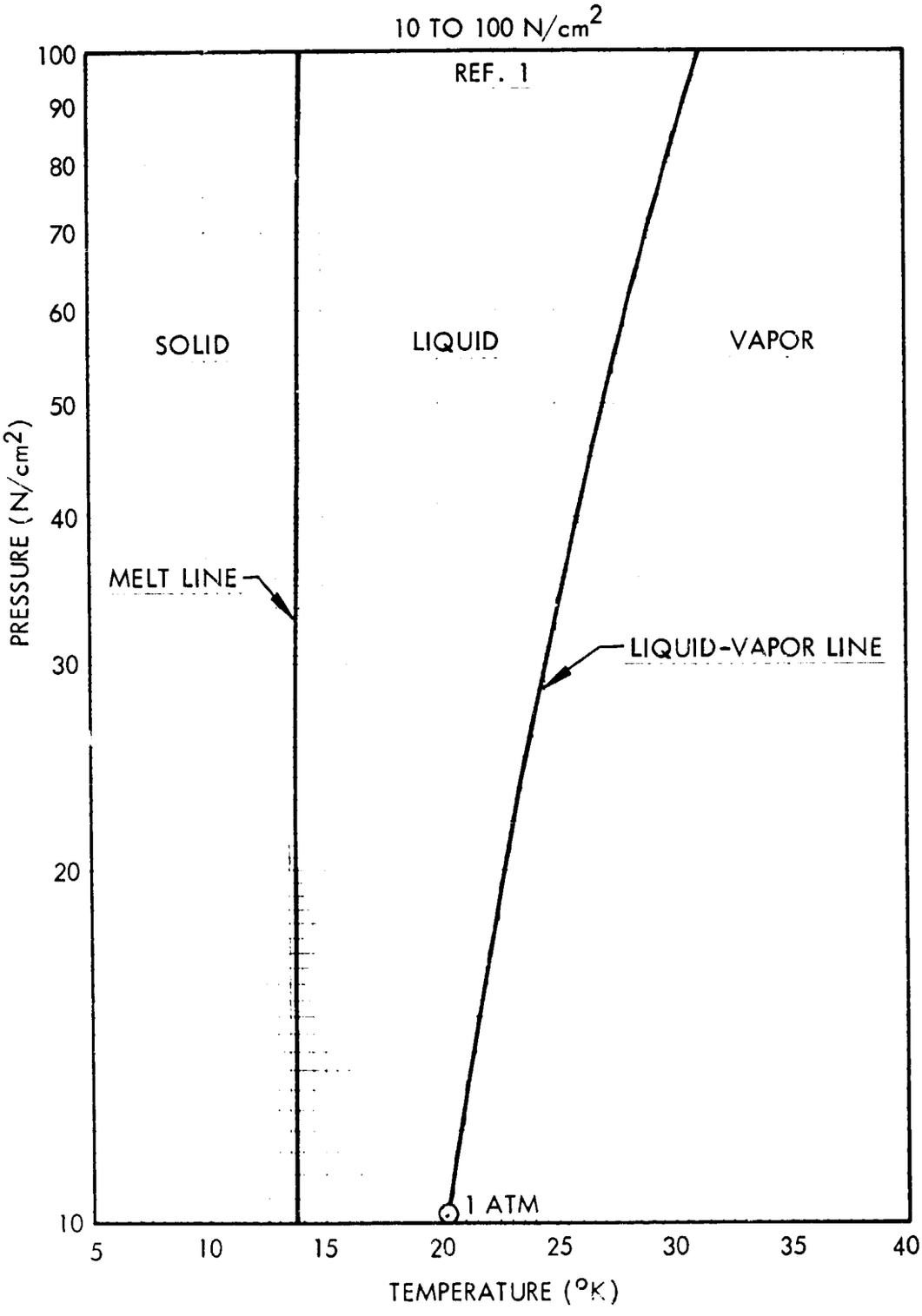

Fig. 3-5 Parahydrogen Pressure-Temperature Phase Diagram (10 to 100 N/cm^2)

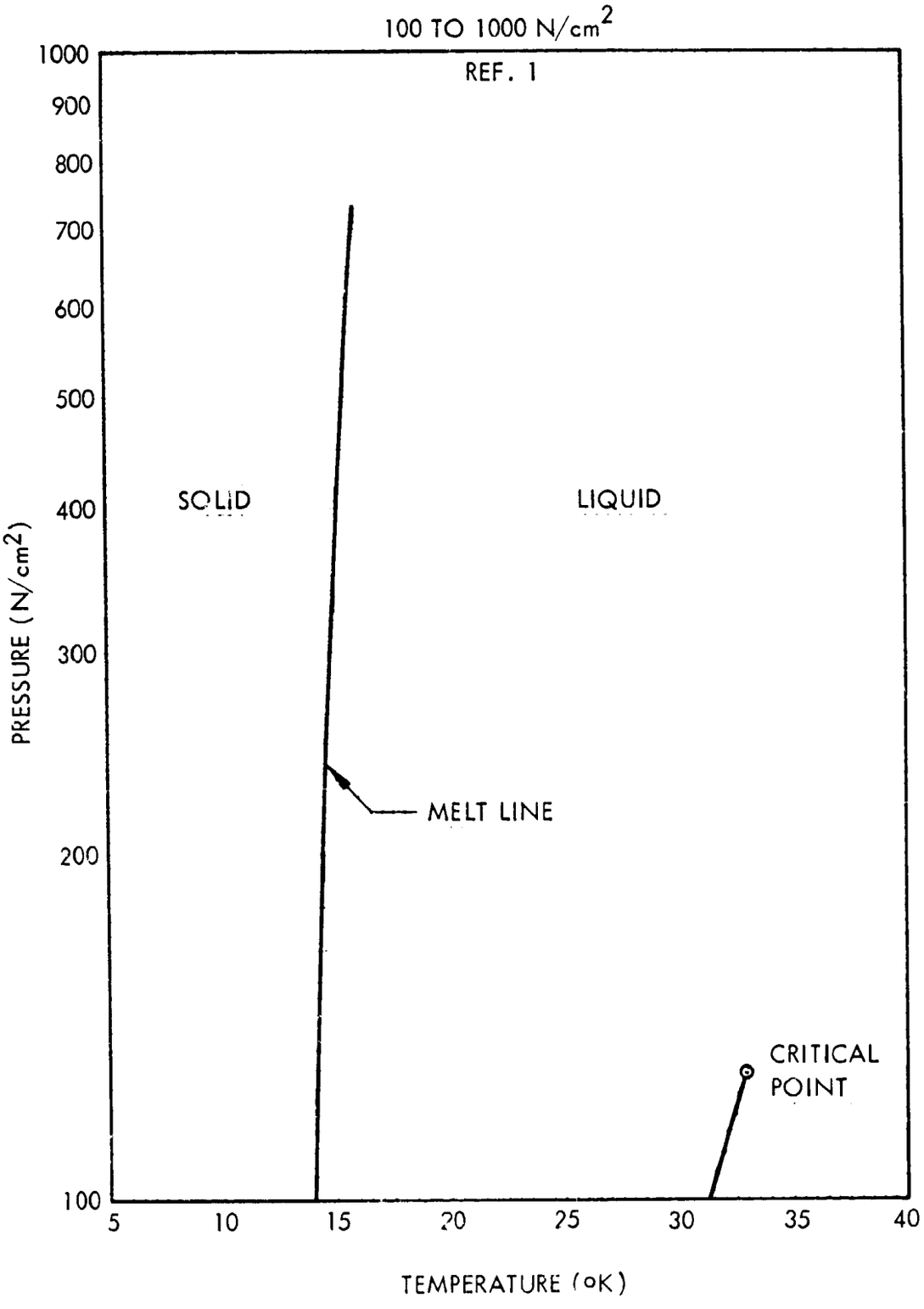

Fig. 3-6 Parahydrogen Pressure-Temperature Phase Diagram (100 to 1000 N/cm^2)

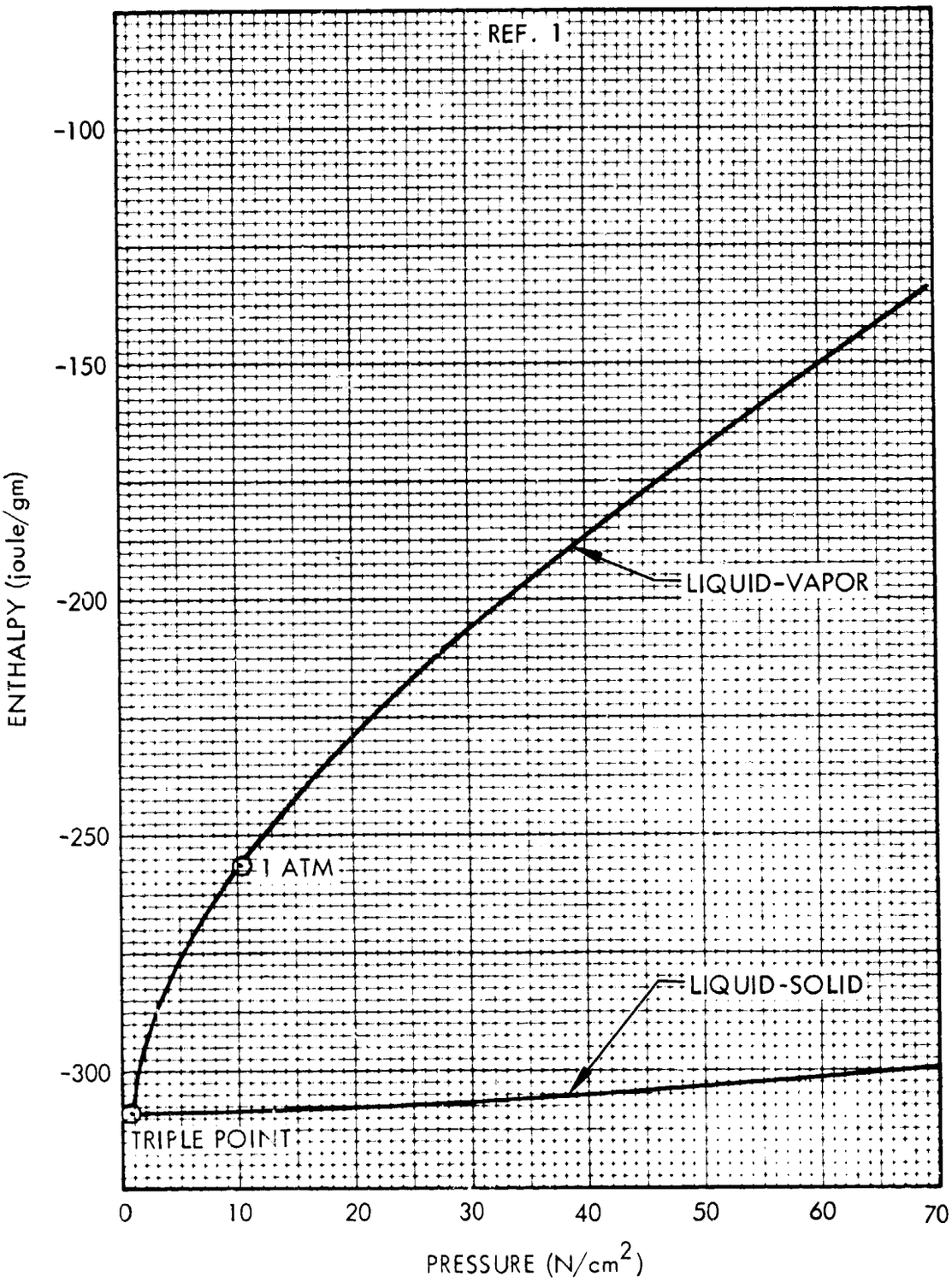

Fig. 3-7 Enthalpy of Saturated Parahydrogen Liquid

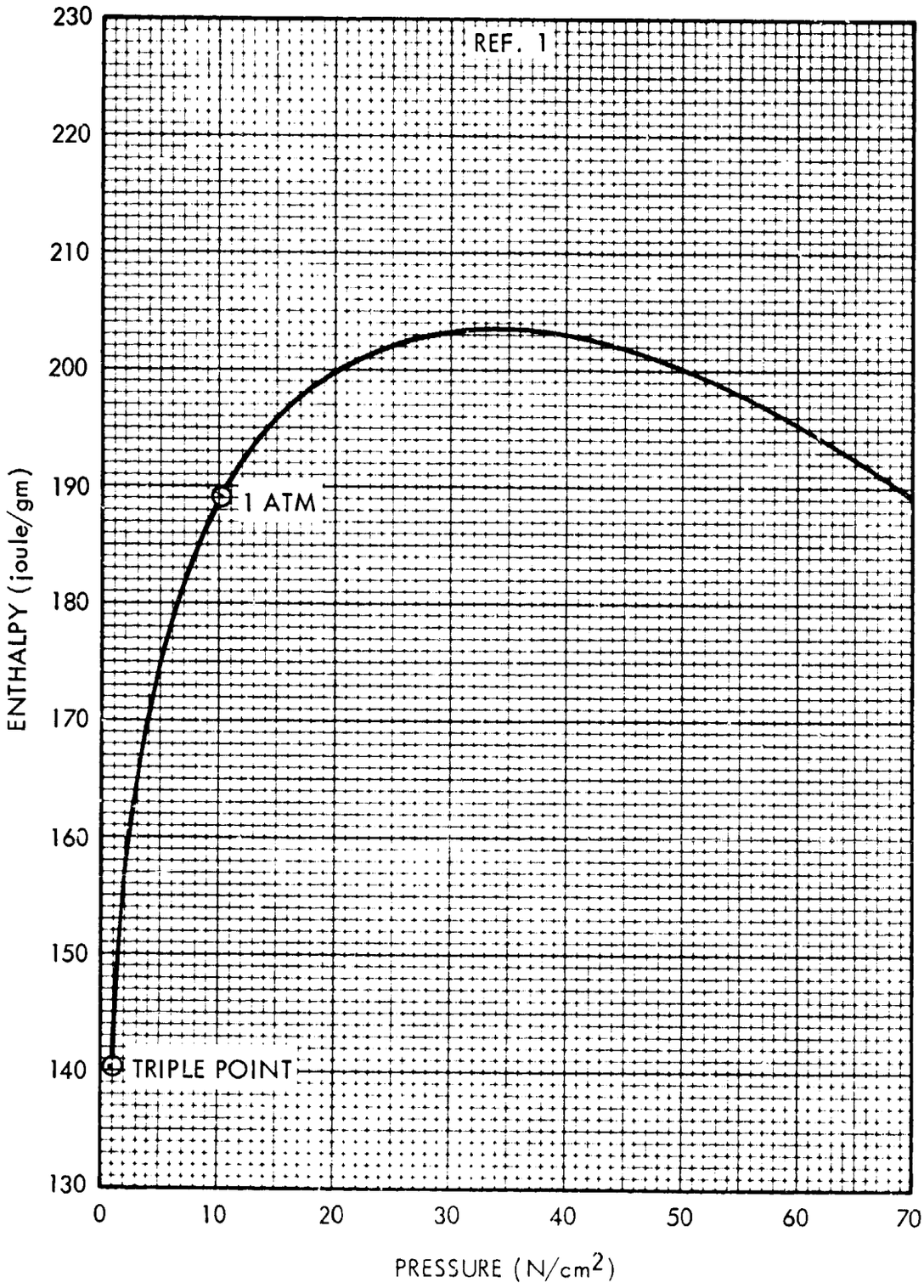

Fig. 3-8 Enthalpy of Saturated Parahydrogen Vapor

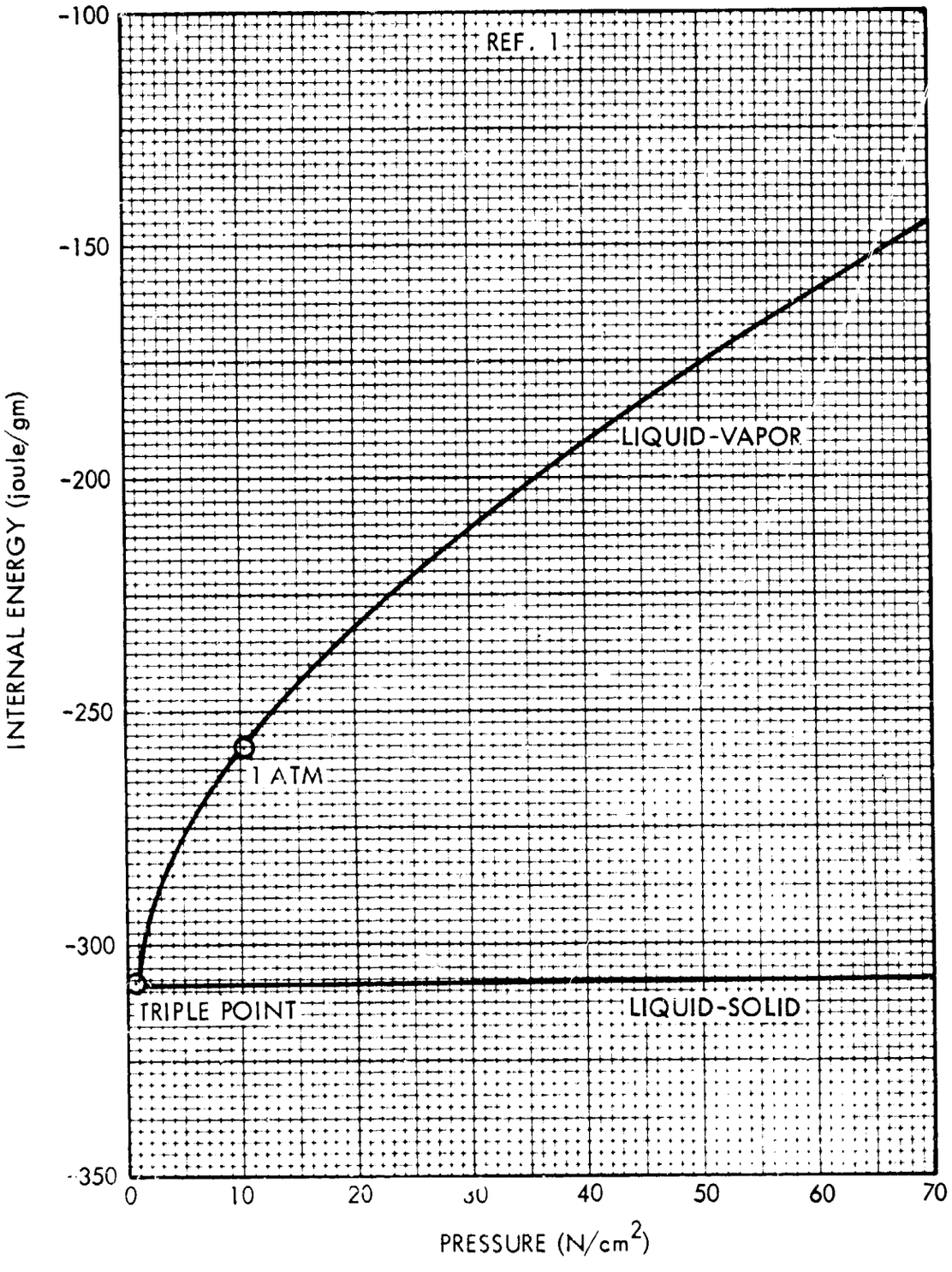

Fig. 3-9 Internal Energy of Saturated Parahydrogen Liquid

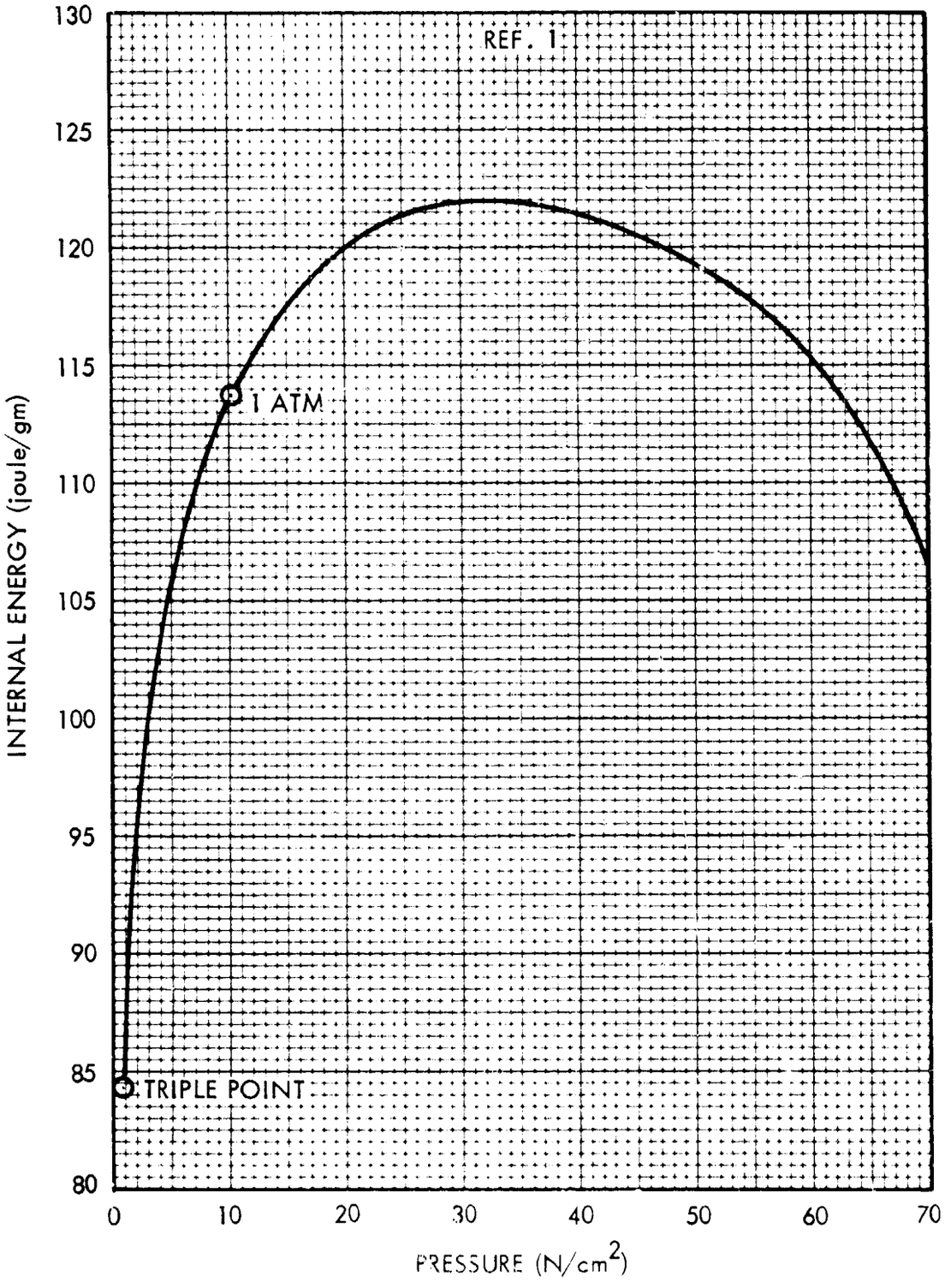

Fig. 3-10 Internal Energy of Saturated Parahydrogen Vapor

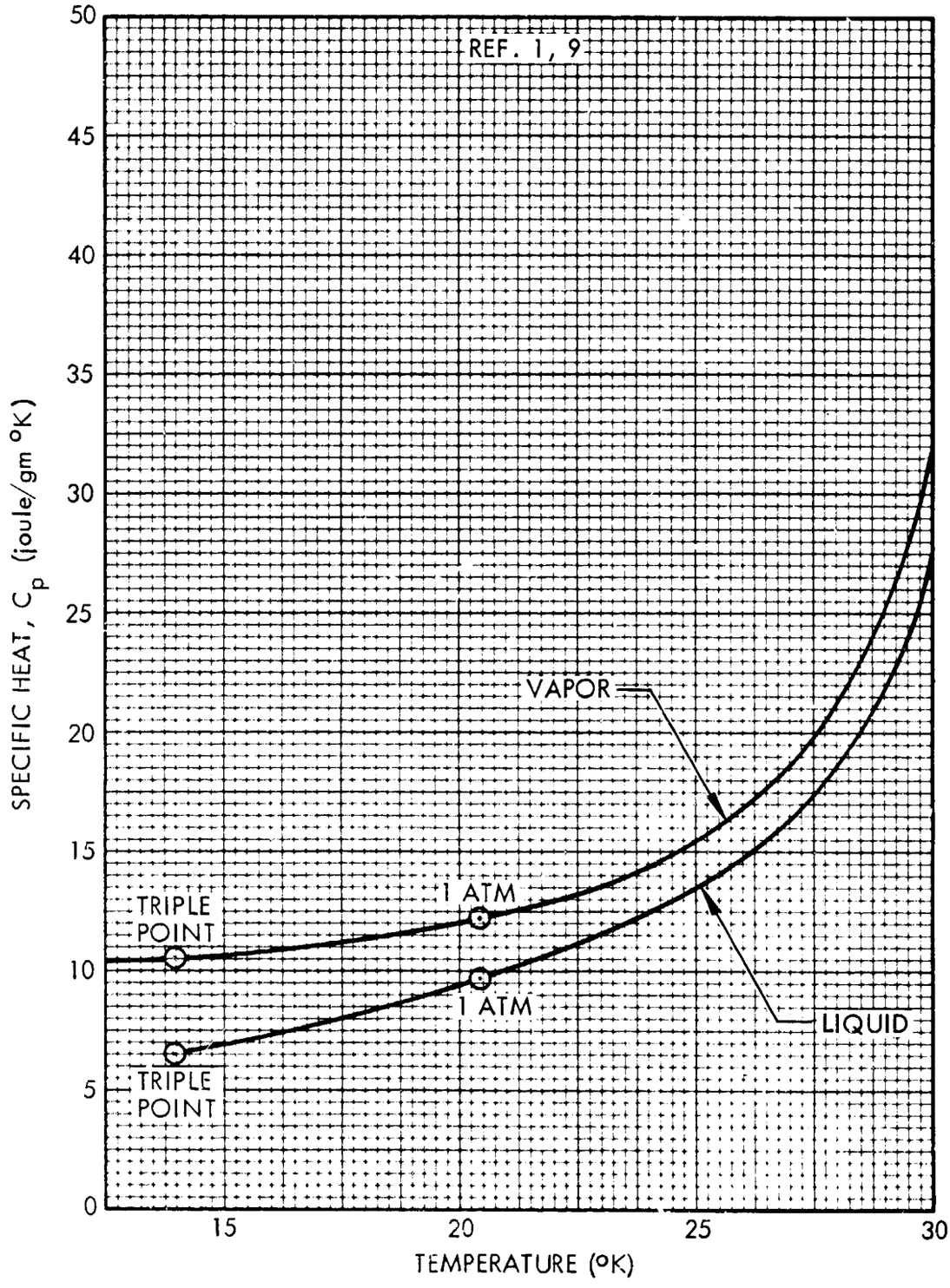

Fig. 3-11 Heat Capacity of Saturated Parahydrogen at Constant Pressure

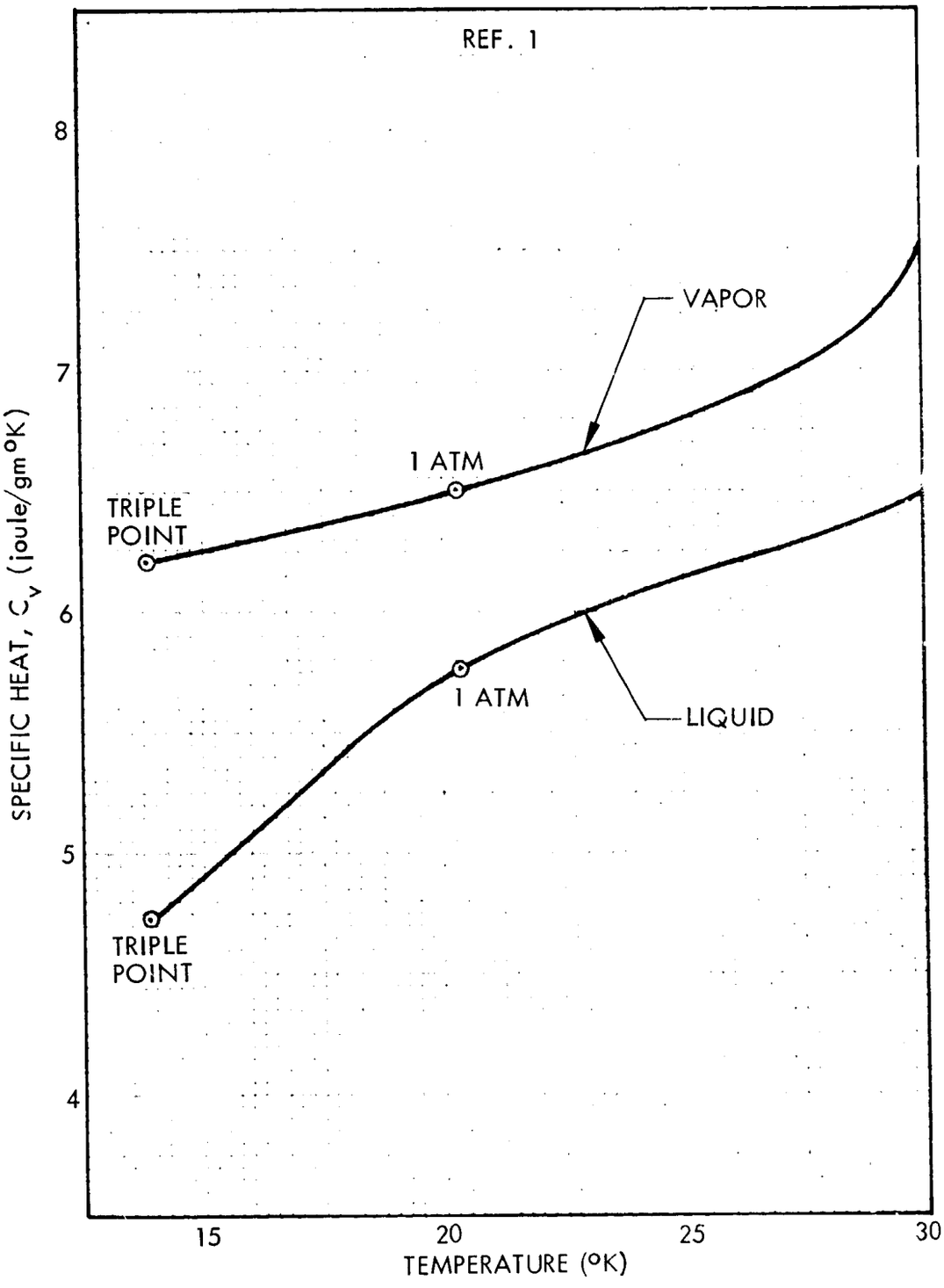

Fig. 3-12 Heat Capacity of Saturated Parahydrogen at Constant Volume

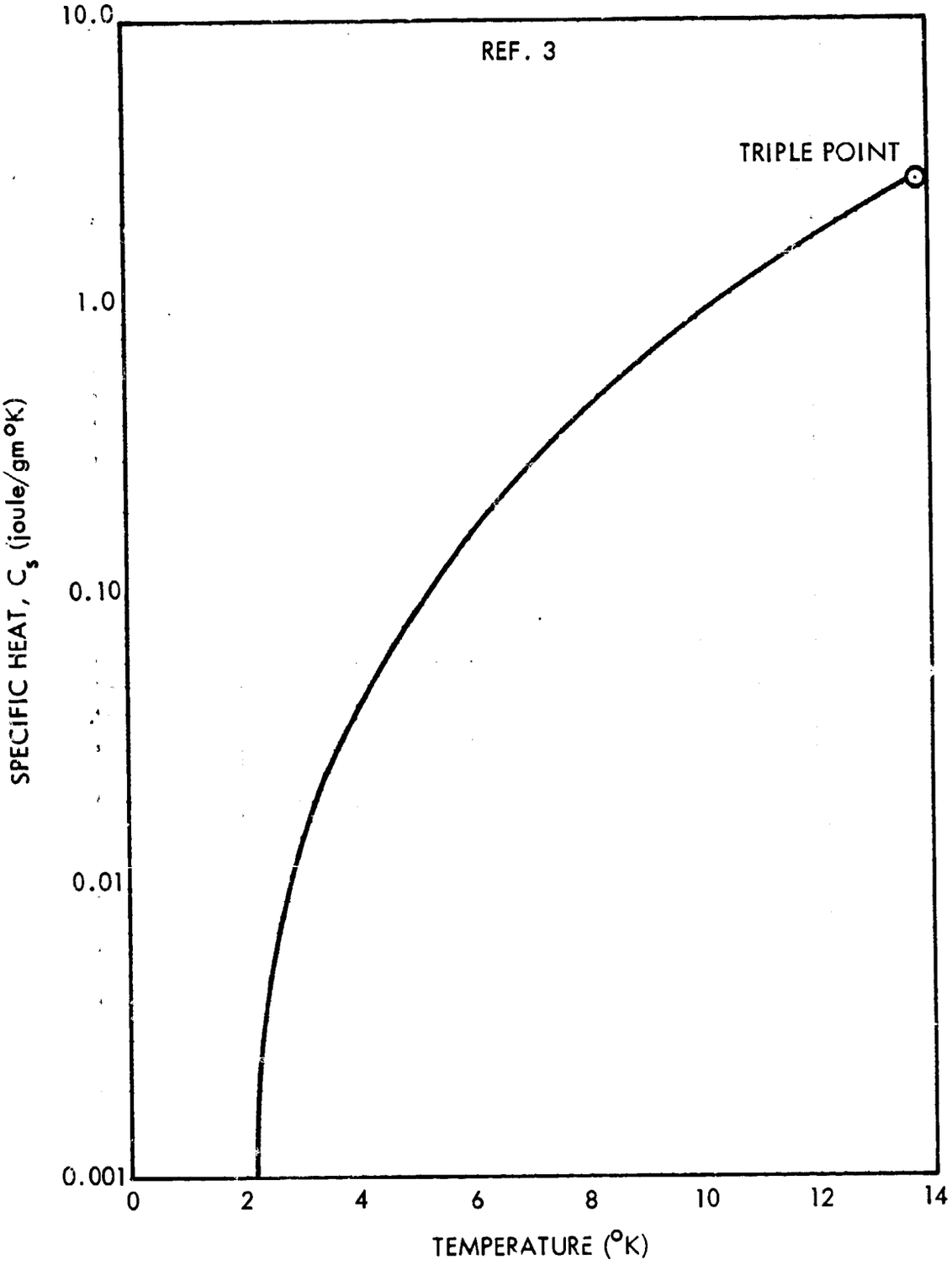

Fig. 3-13 Heat Capacity (C_s) of Saturated Solid Parahydrogen

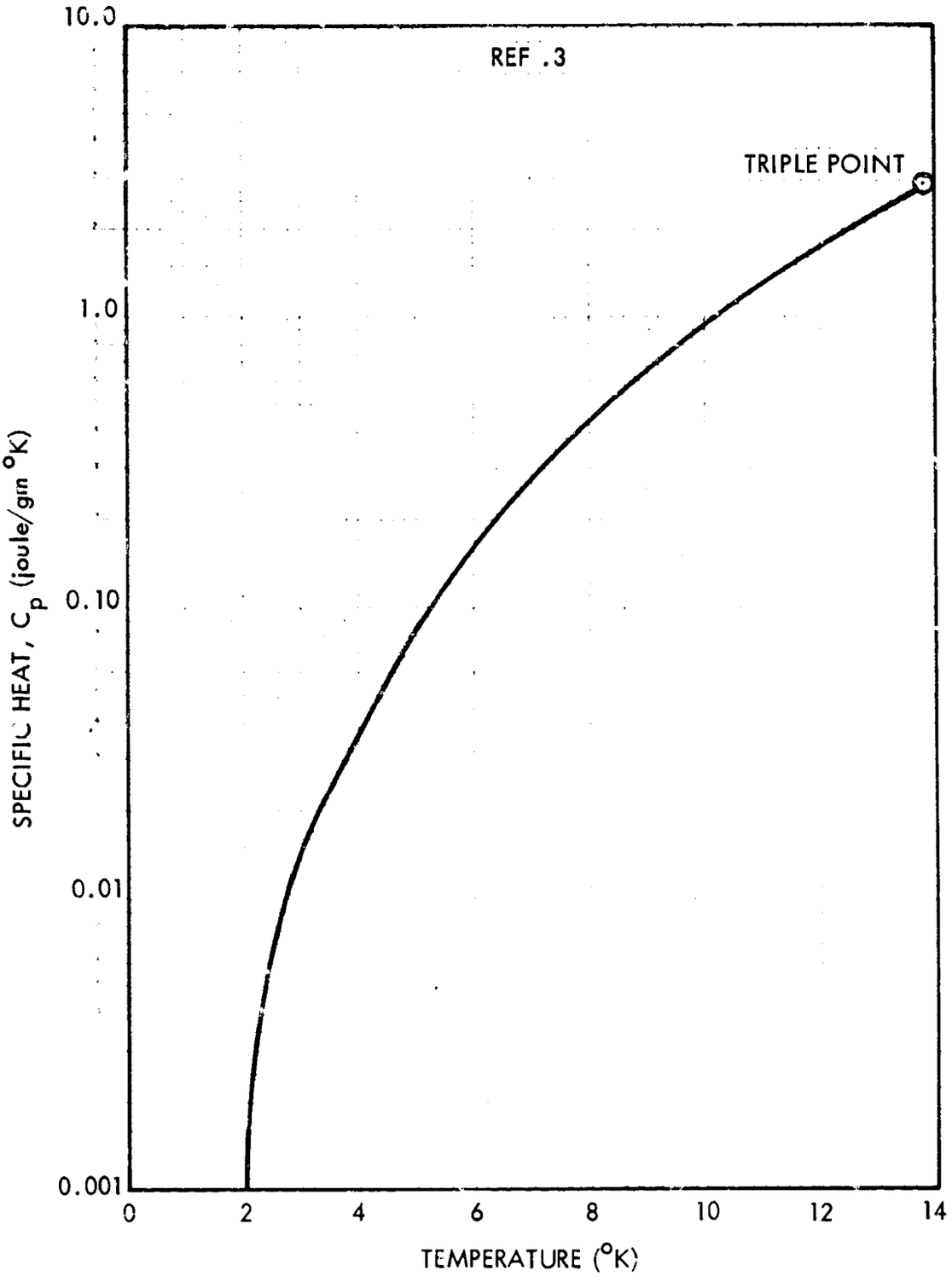

Fig. 3-14 Heat Capacity (C_p) of Saturated Solid Parahydrogen

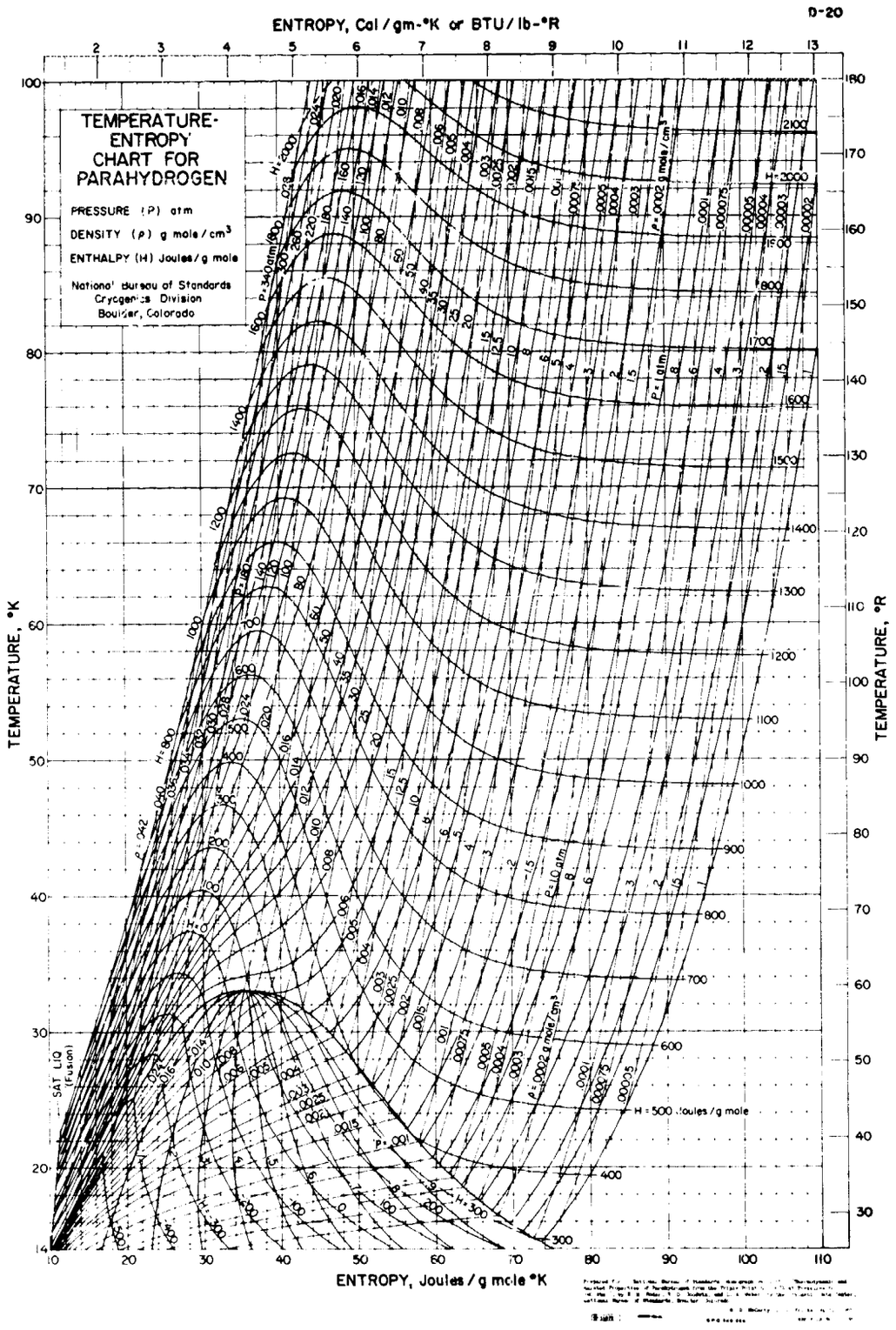

Fig. 3-15 Temperature-Entropy Diagram (International Units)
(From NBS File D5881, April 1965)

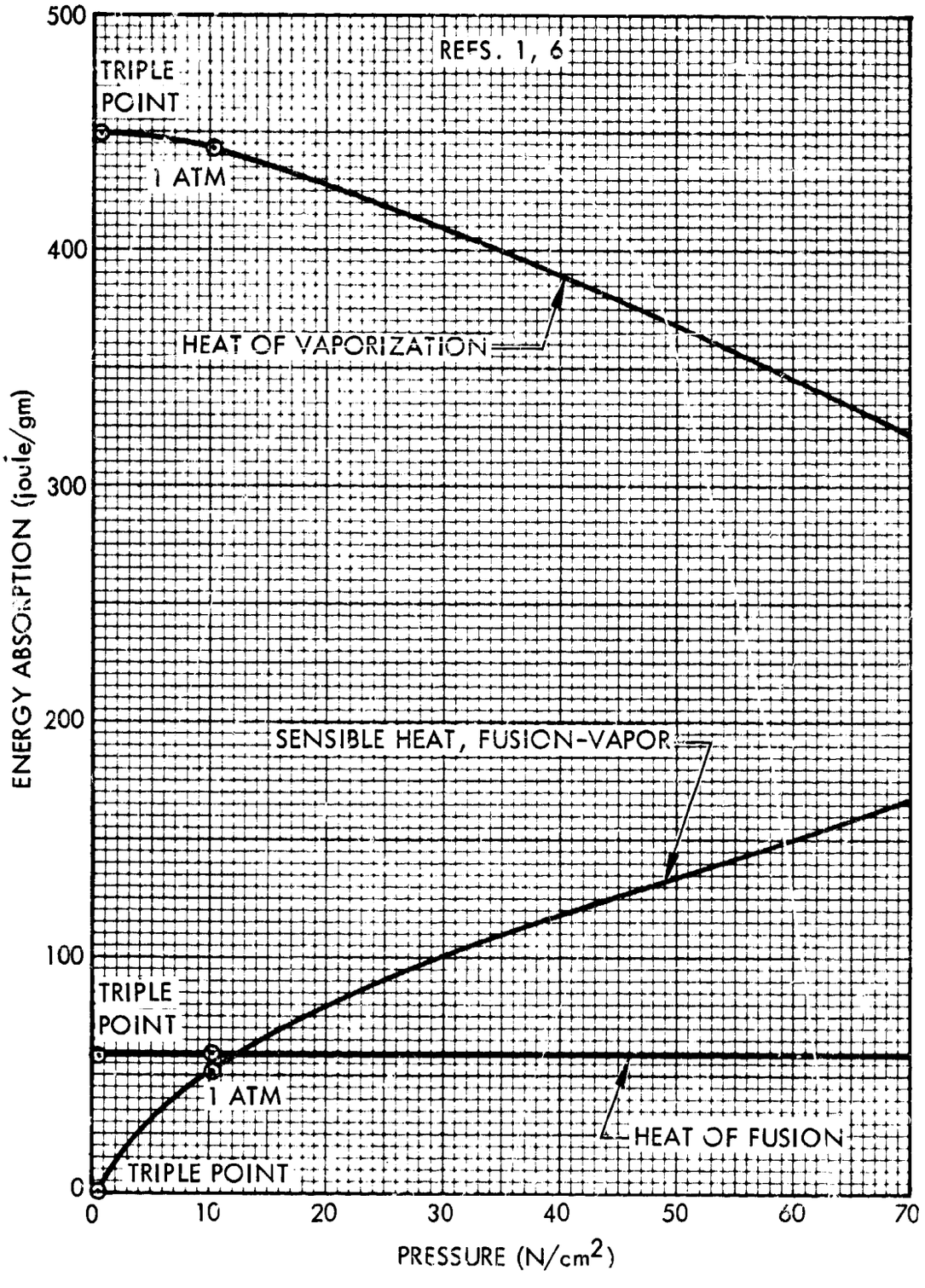

Fig. 3-16 Energy Absorption Capability of Saturated Parahydrogen

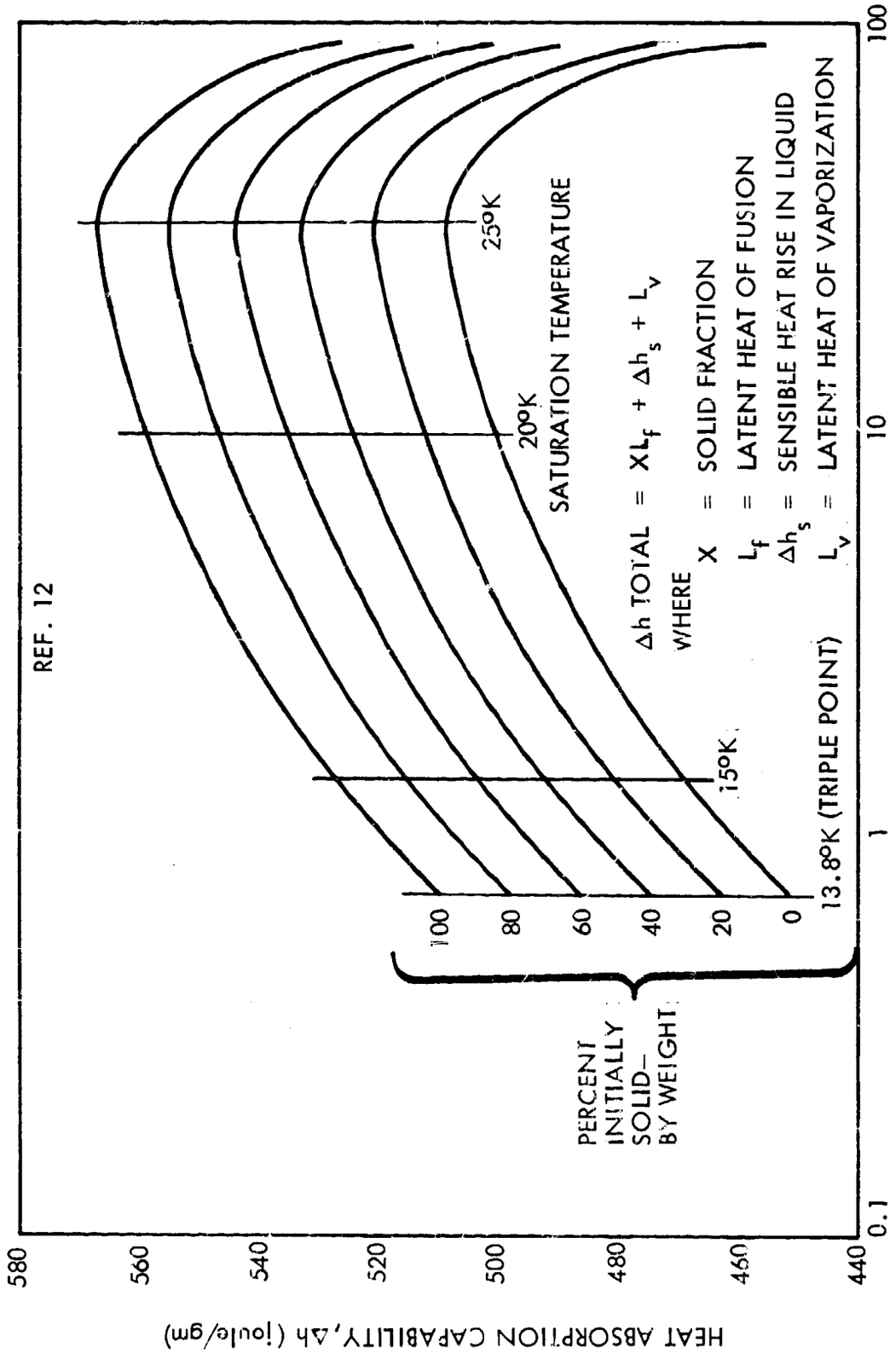

Fig. 3-17 Energy Absorption Capability of Liquid-Solid Mixtures of Parahydrogen

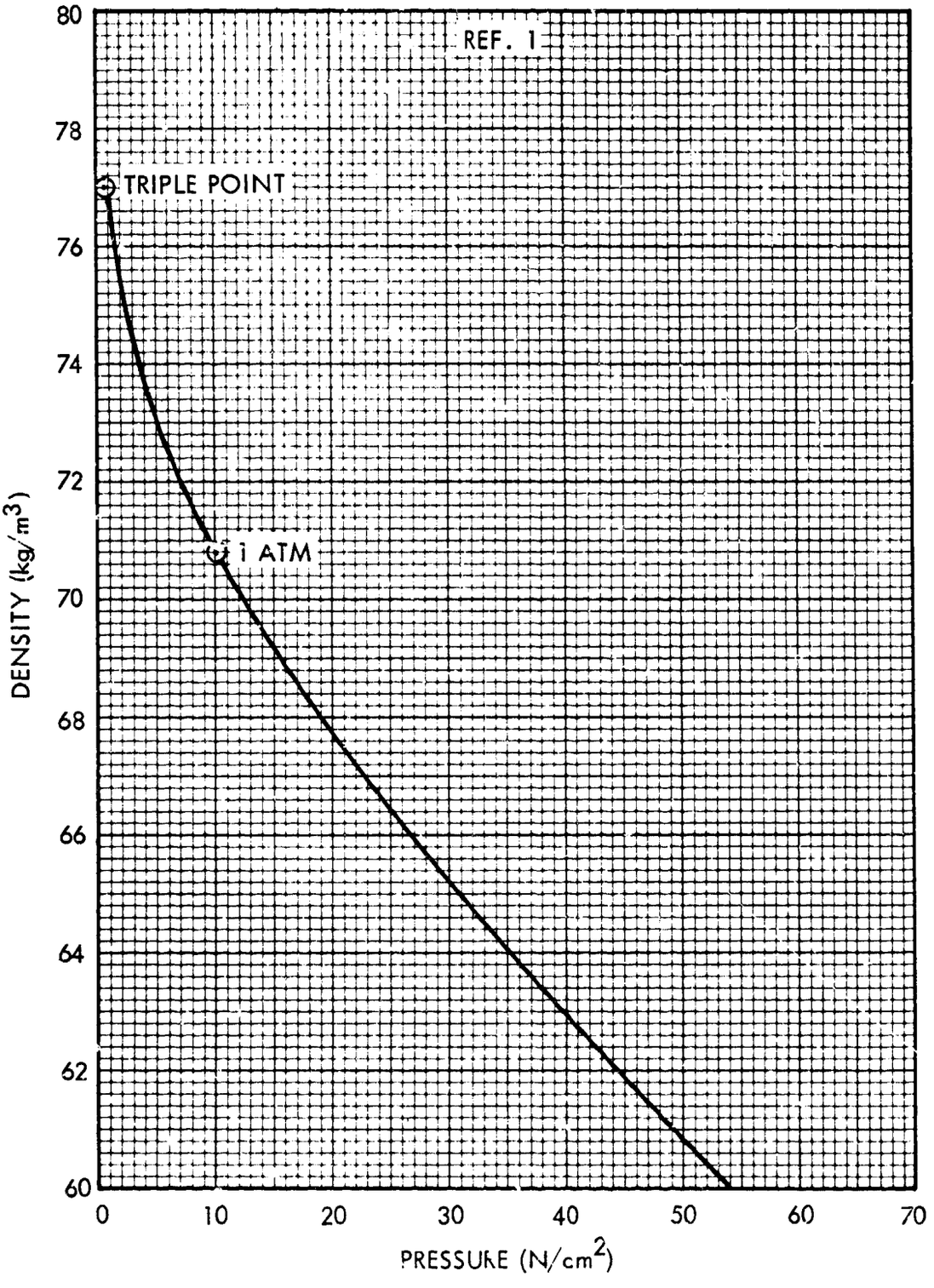

Fig. 3-18 Density of Saturated Parahydrogen Liquid

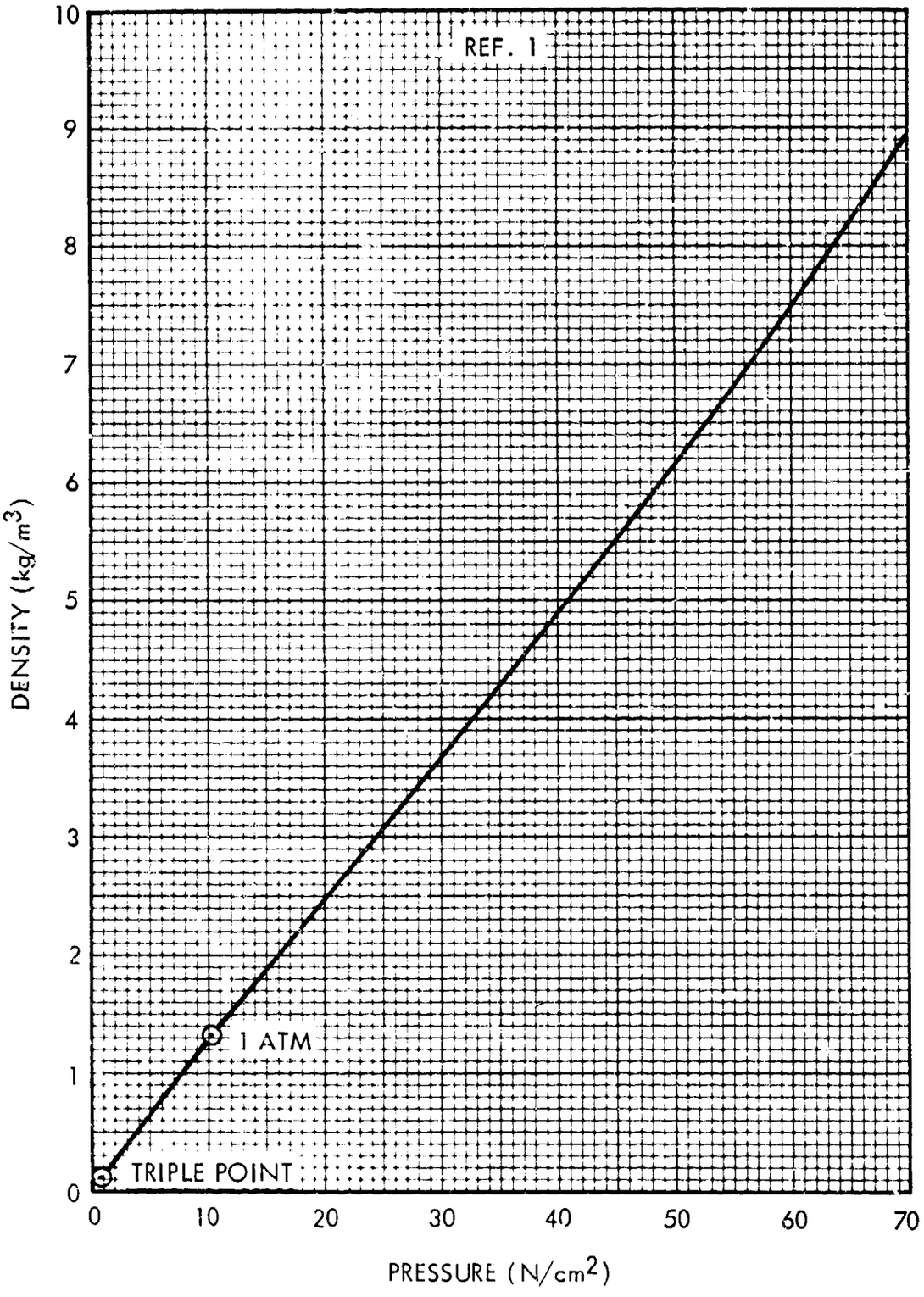

Fig. 3-19 Density of Saturated Parahydrogen Vapor

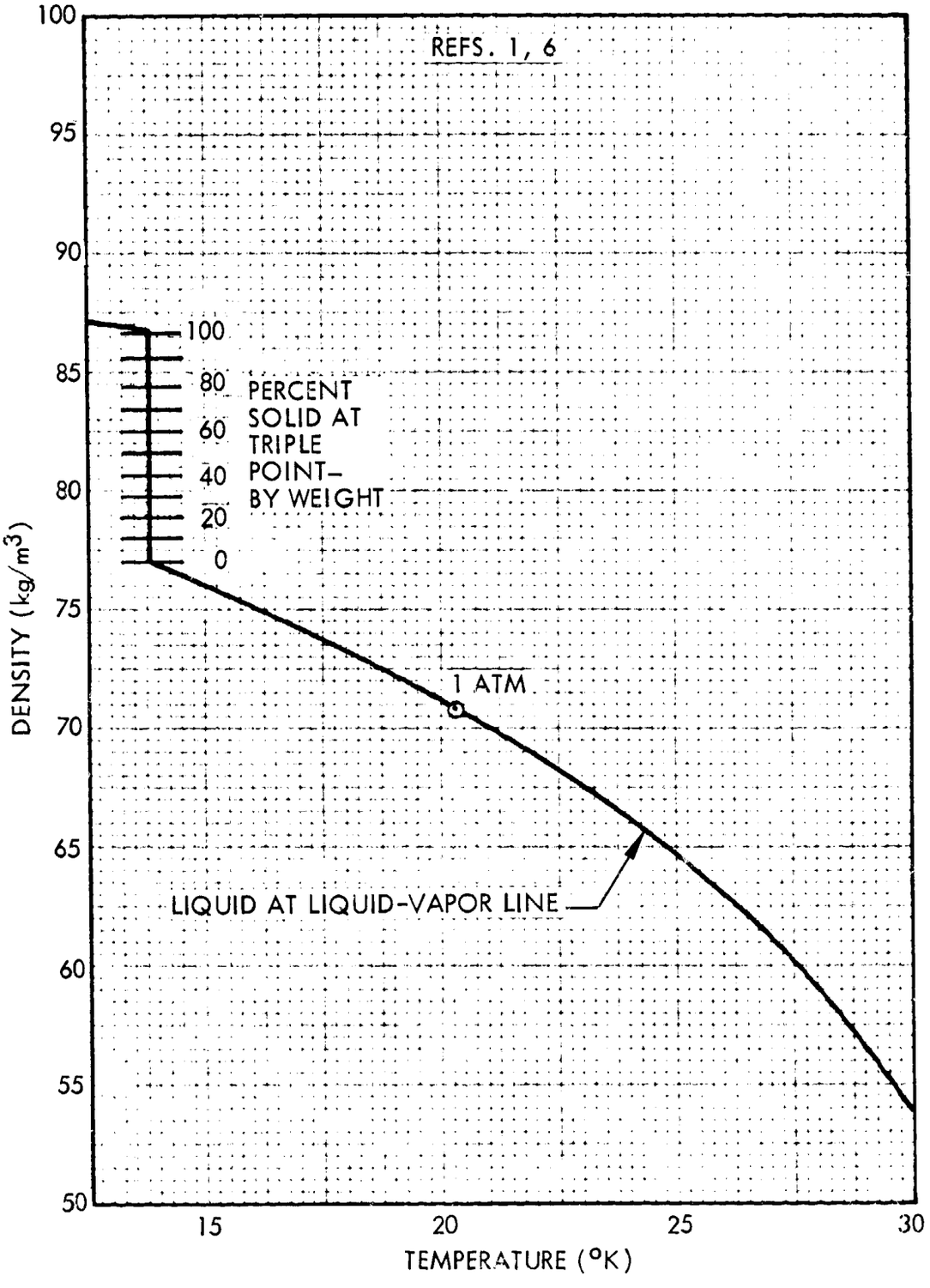

Fig. 3-20 Density of Liquid and Solid-Liquid Mixtures of Saturated Parahydrogen

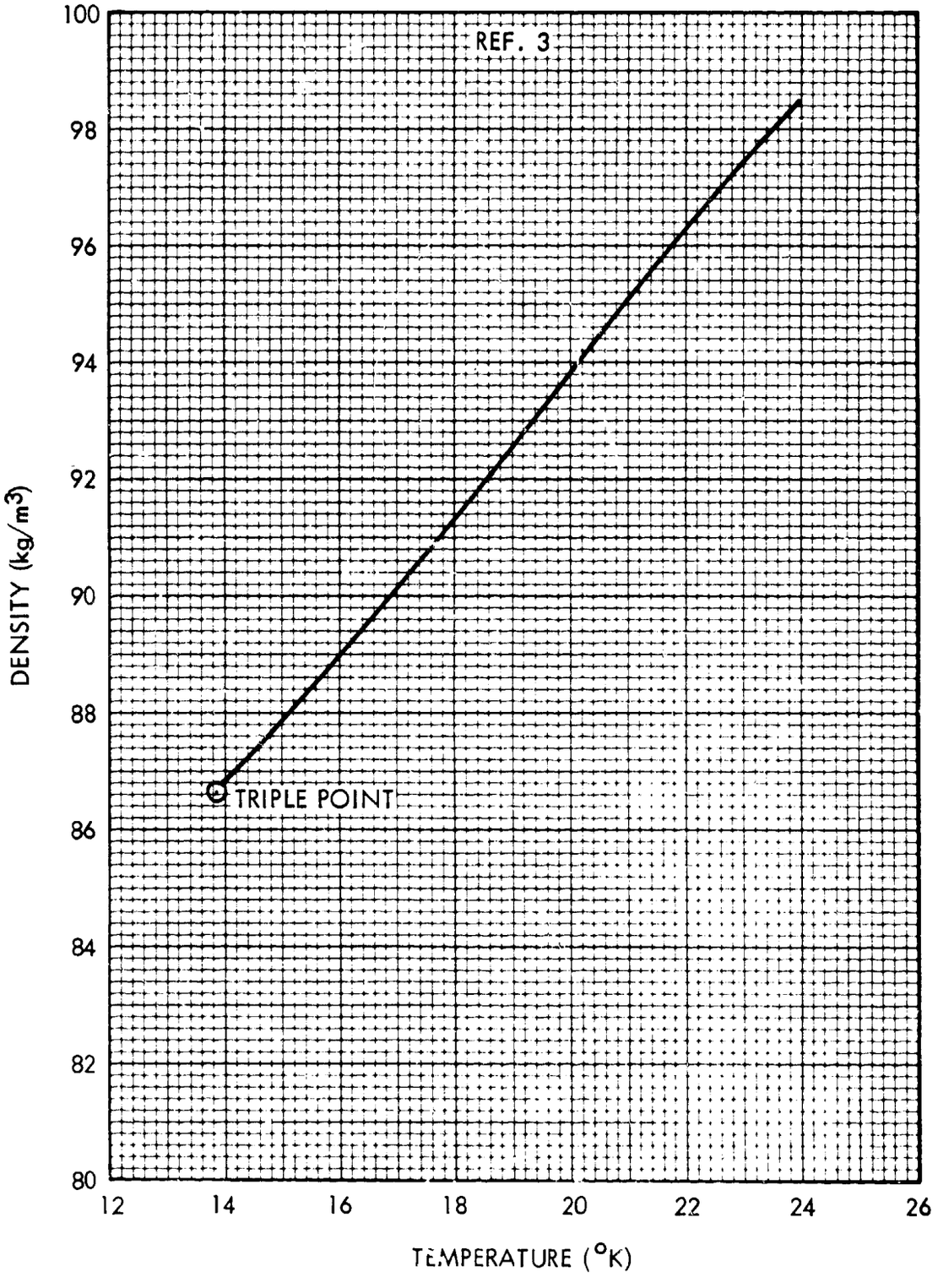

Fig. 3-21 Density of Solid Parahydrogen Along the Melting Line

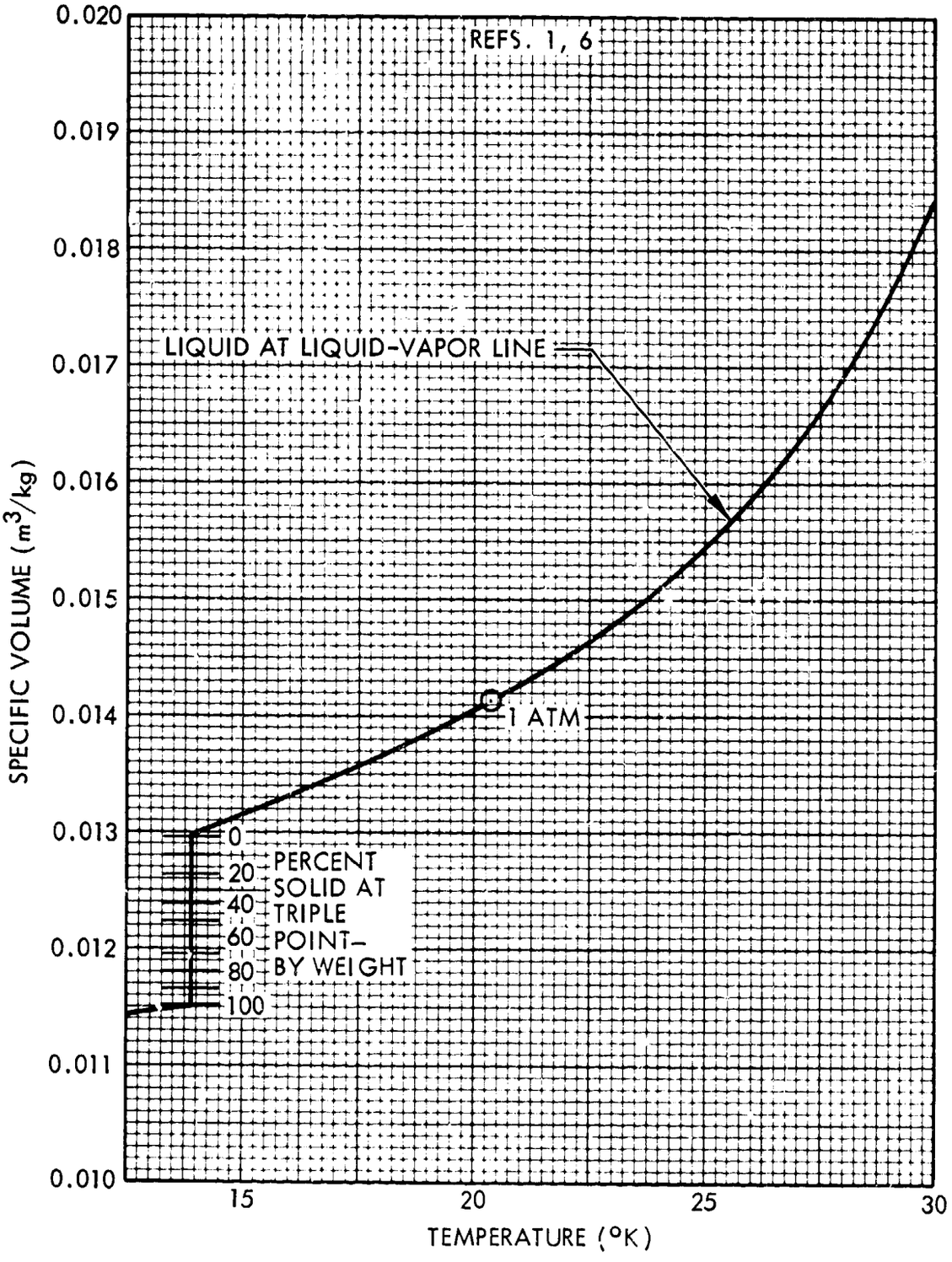

Fig. 3-22 Specific Volume of Liquid and Solid-Liquid Mixtures of Saturated Parahydrogen

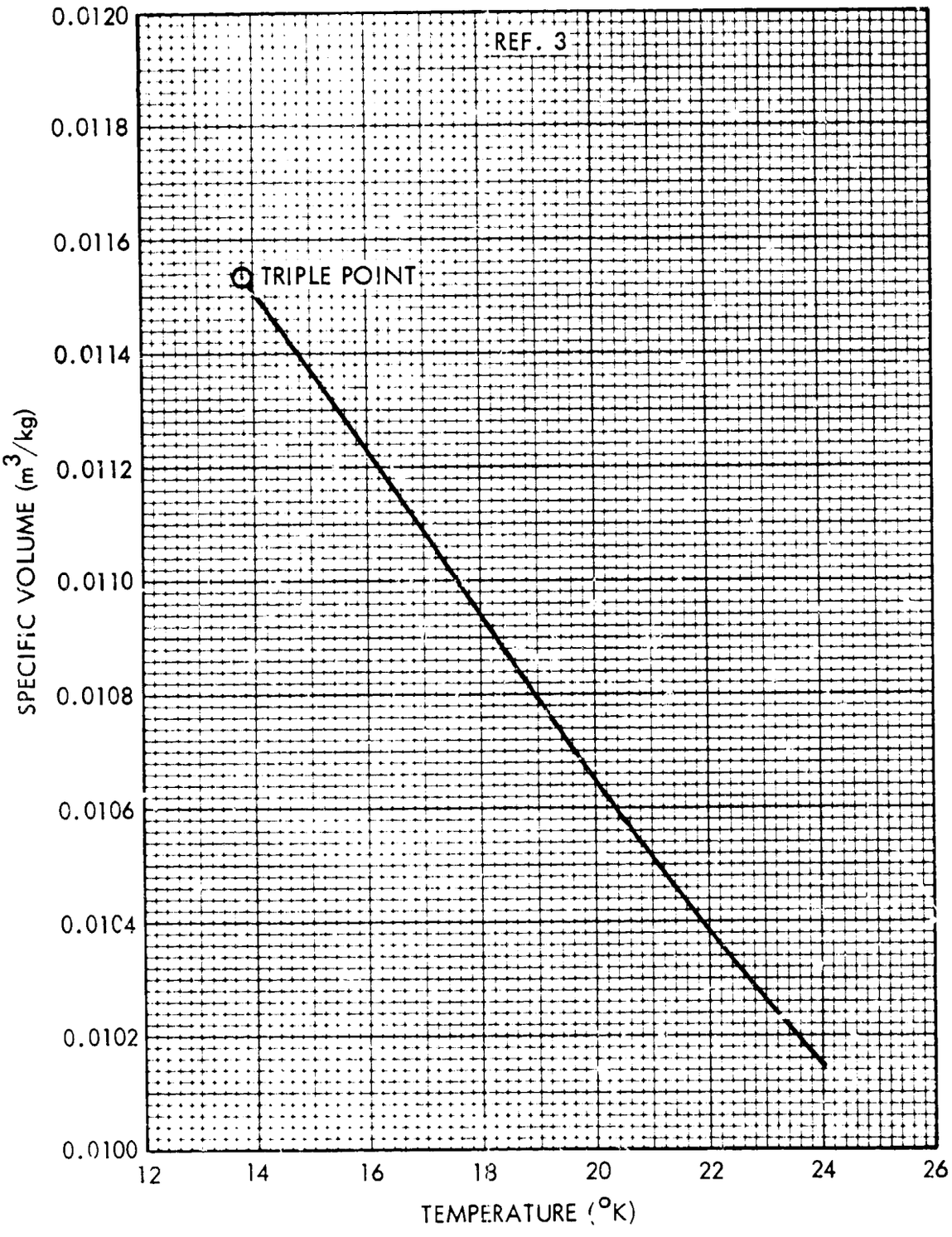

Fig. 3-23 Specific Volume of Solid Parahydrogen Along the Melting Line

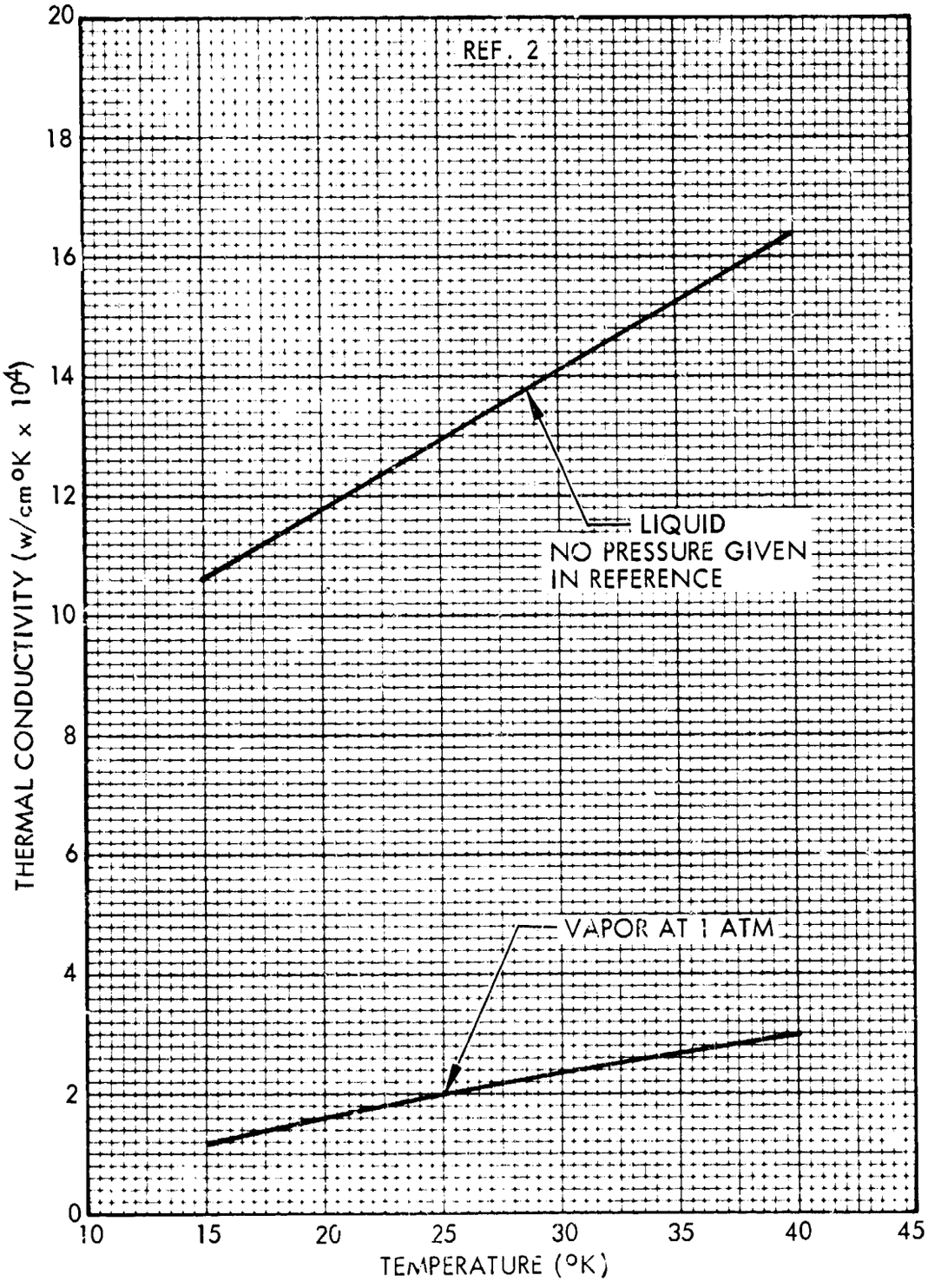

Fig. 3-24 Thermal Conductivity of Parahydrogen Liquid and Vapor

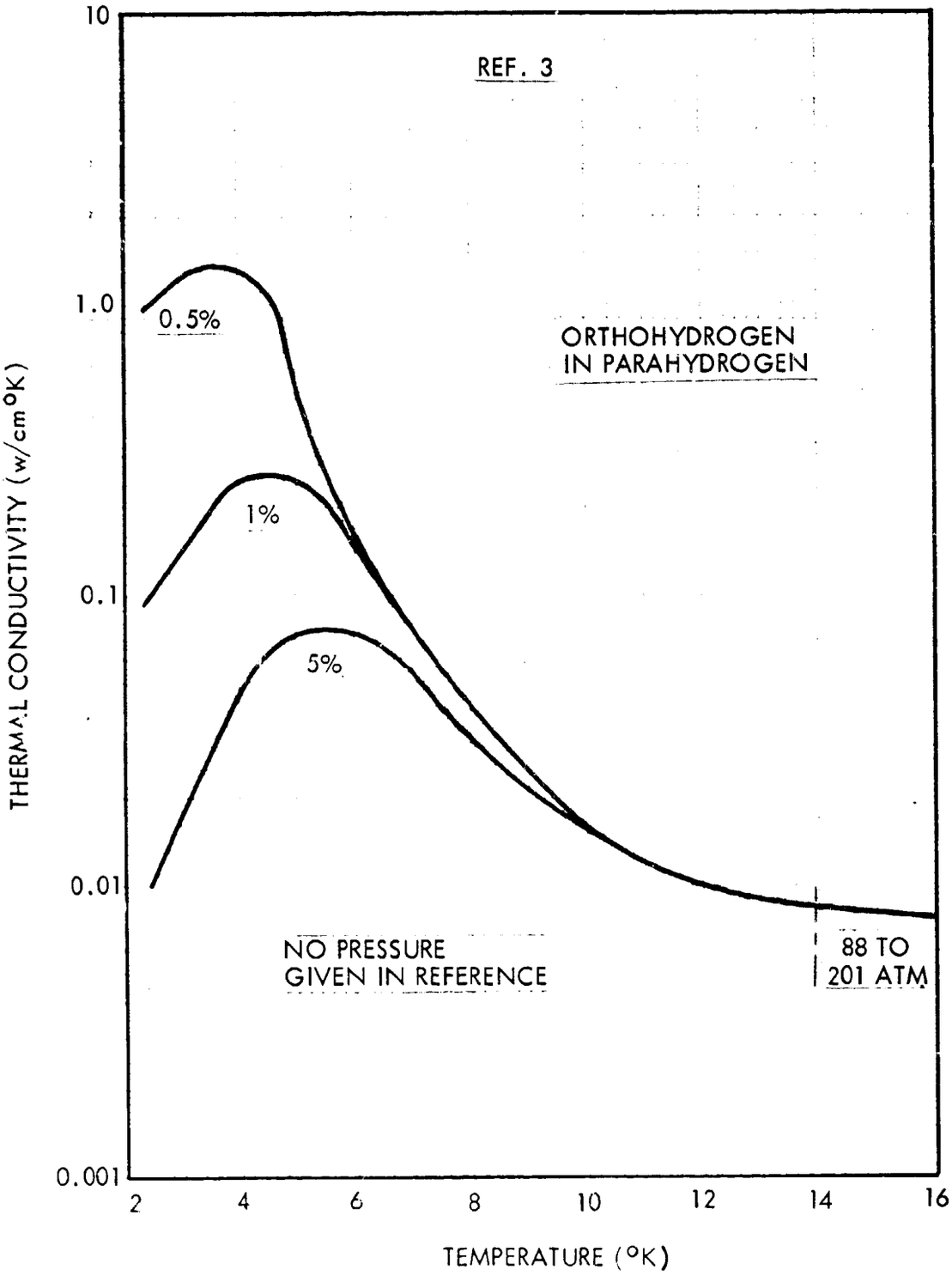

Fig. 3-25 Thermal Conductivity of Parahydrogen Solid

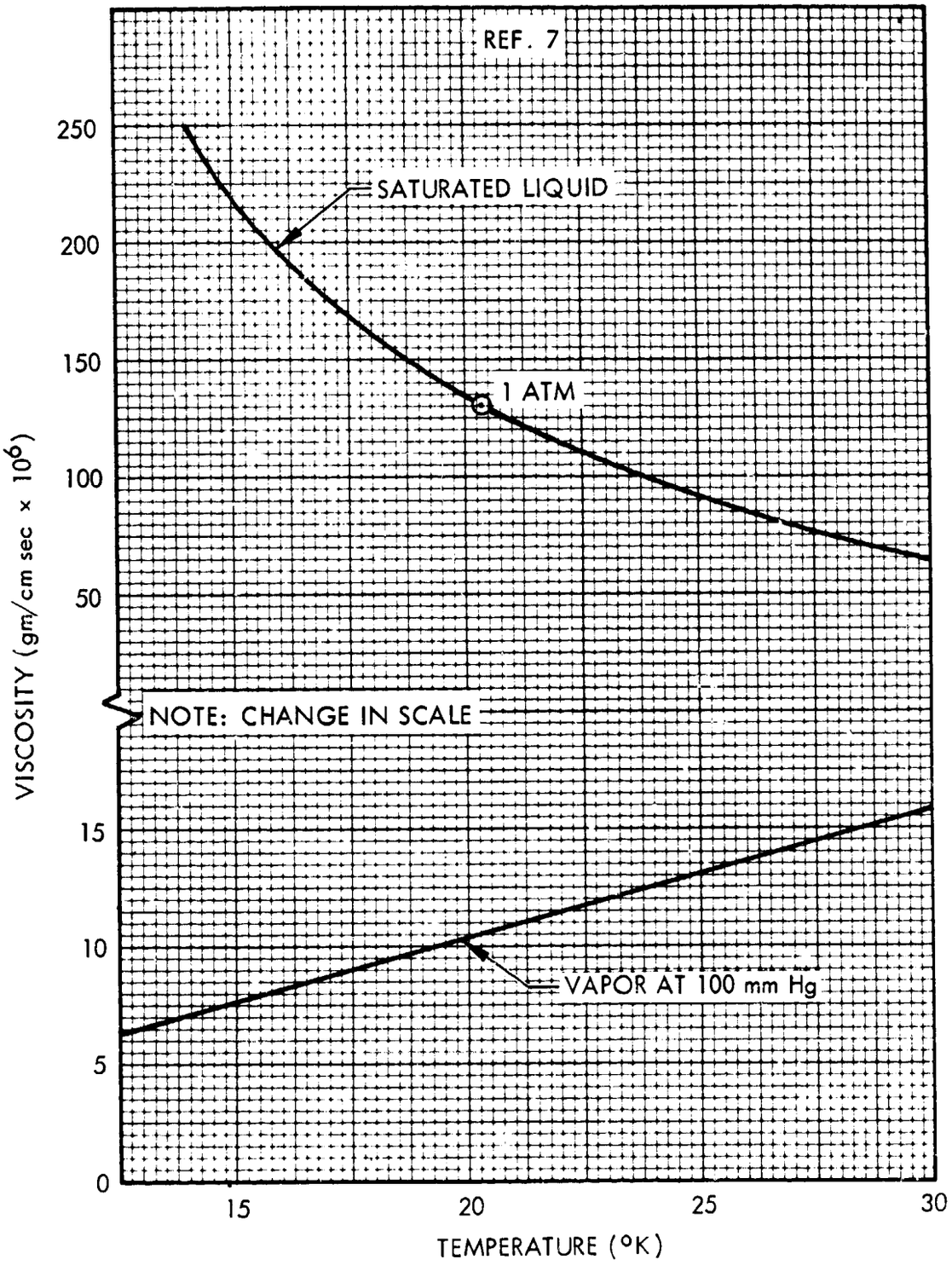

Fig. 3-26 Viscosity of Parahydrogen

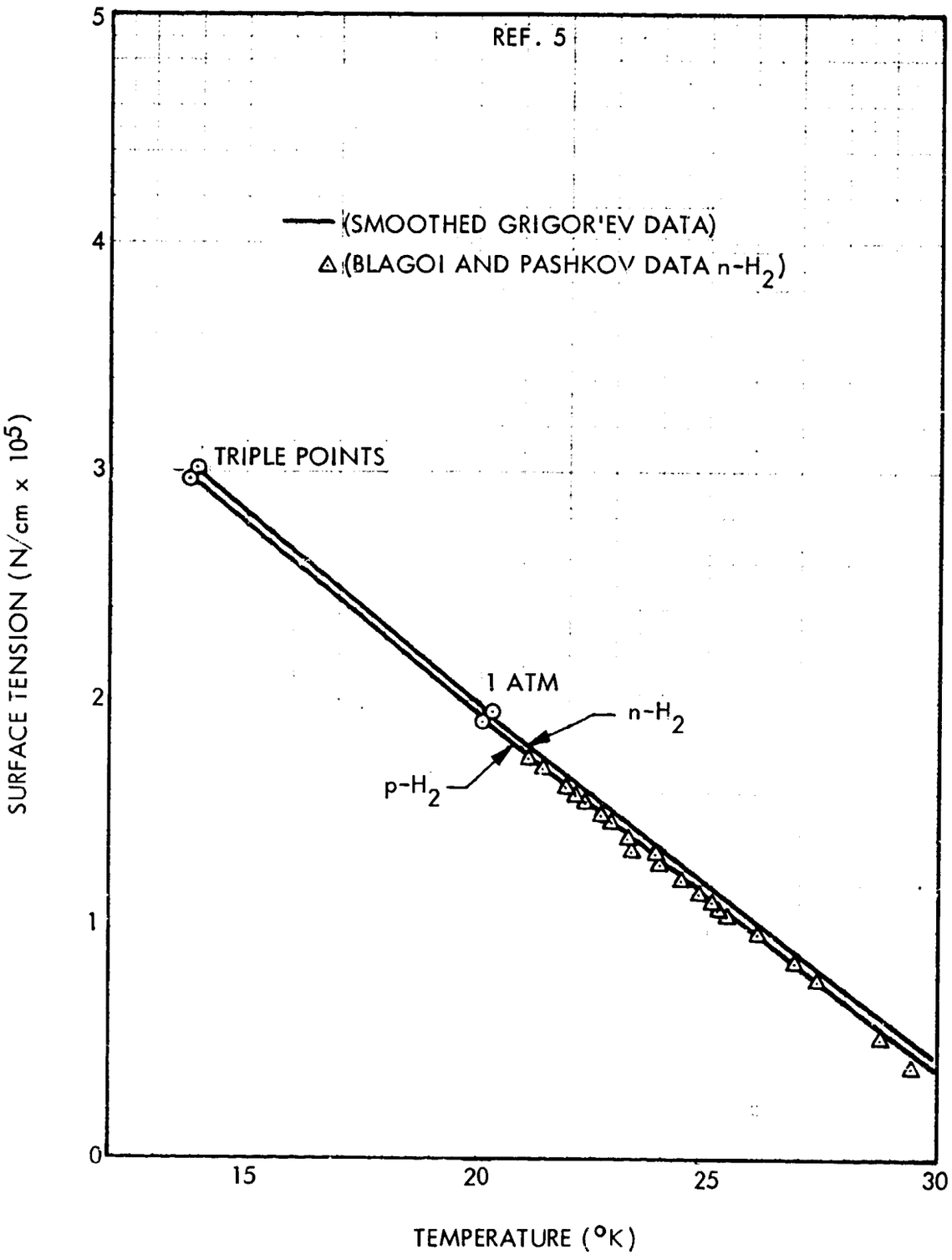

Fig. 3-27 Surface Tension Properties of Parahydrogen

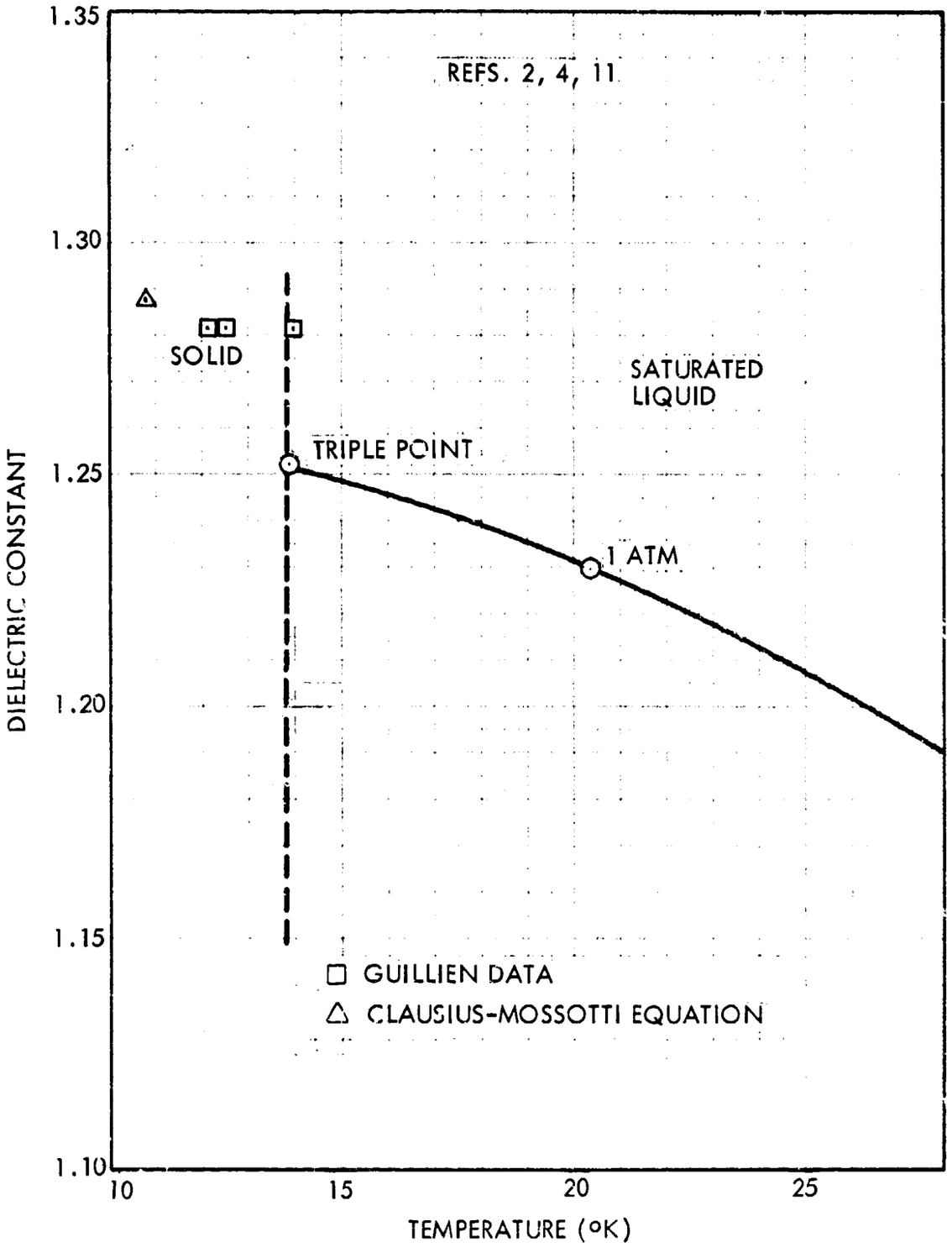

Fig. 3-28 Dielectric Constant of Parahydrogen Solid and Liquid

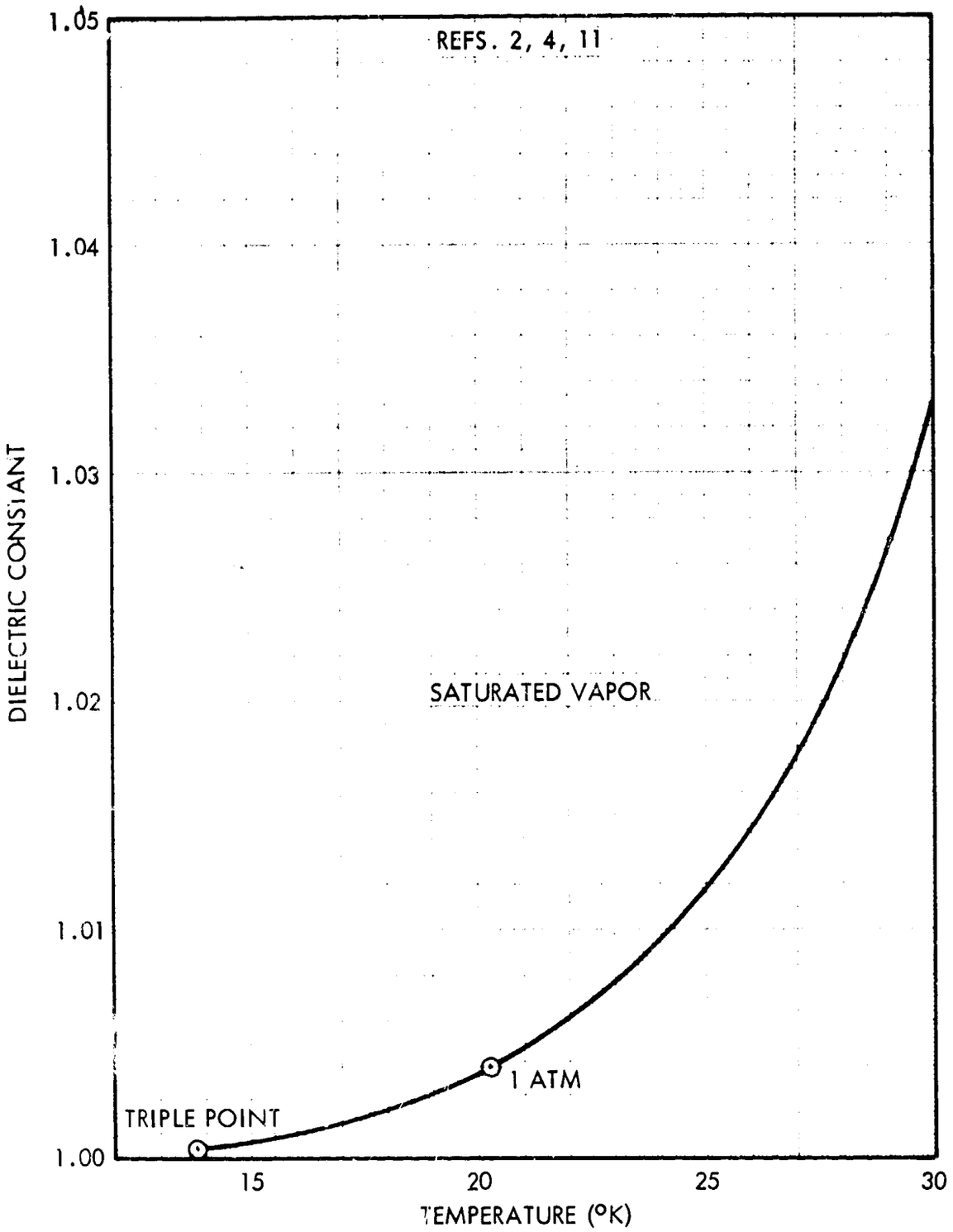

Fig. 3-29 Dielectric Constant of Parahydrogen Vapor

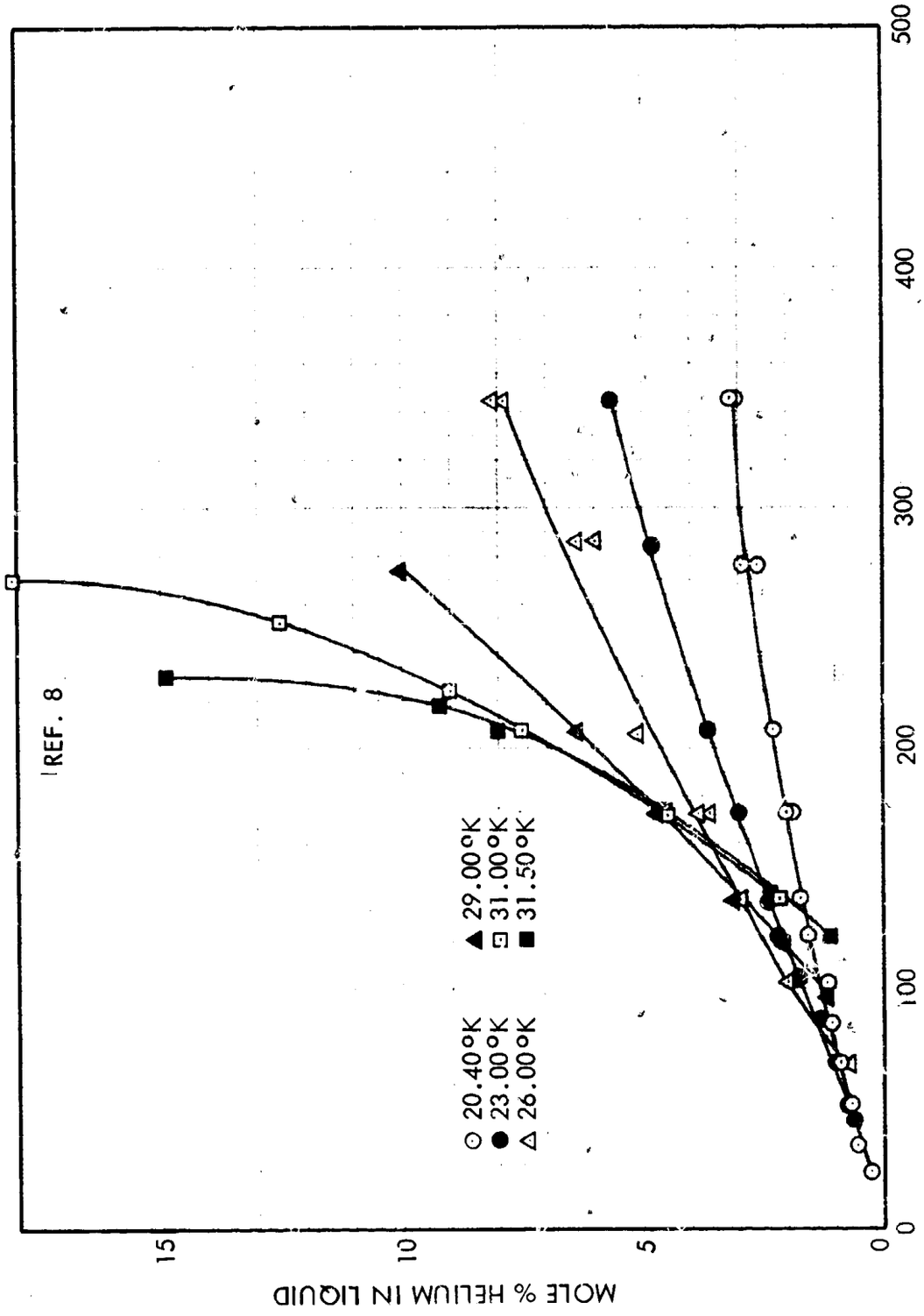

Fig. 3-30 Solubility of Helium Vapor in Equilibrium Hydrogen Liquid

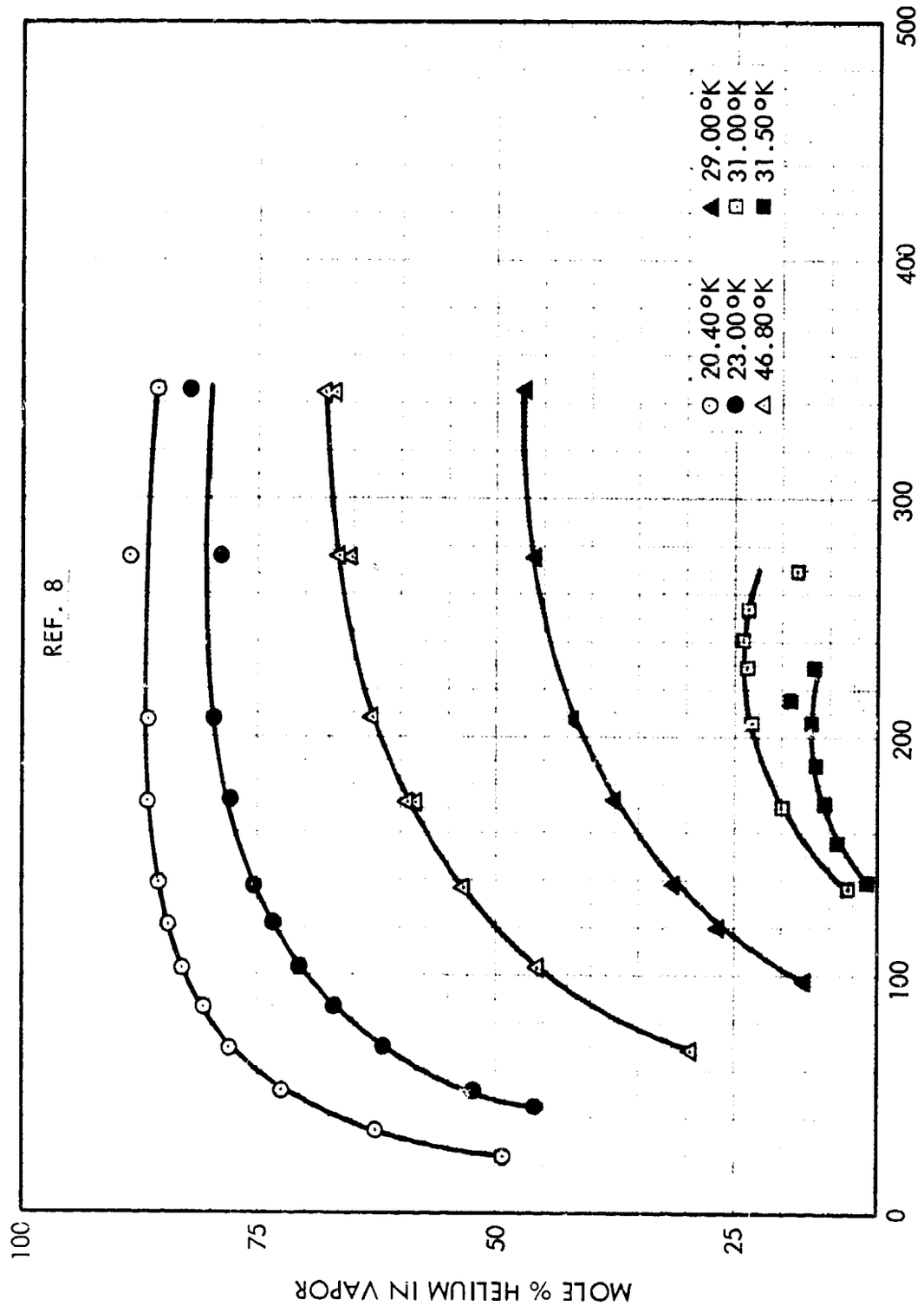

Fig. 3-31 Isothermal Pressure – Composition Diagram for 20.4°K Equilibrium Hydrogen Vapor – Helium Vapor System

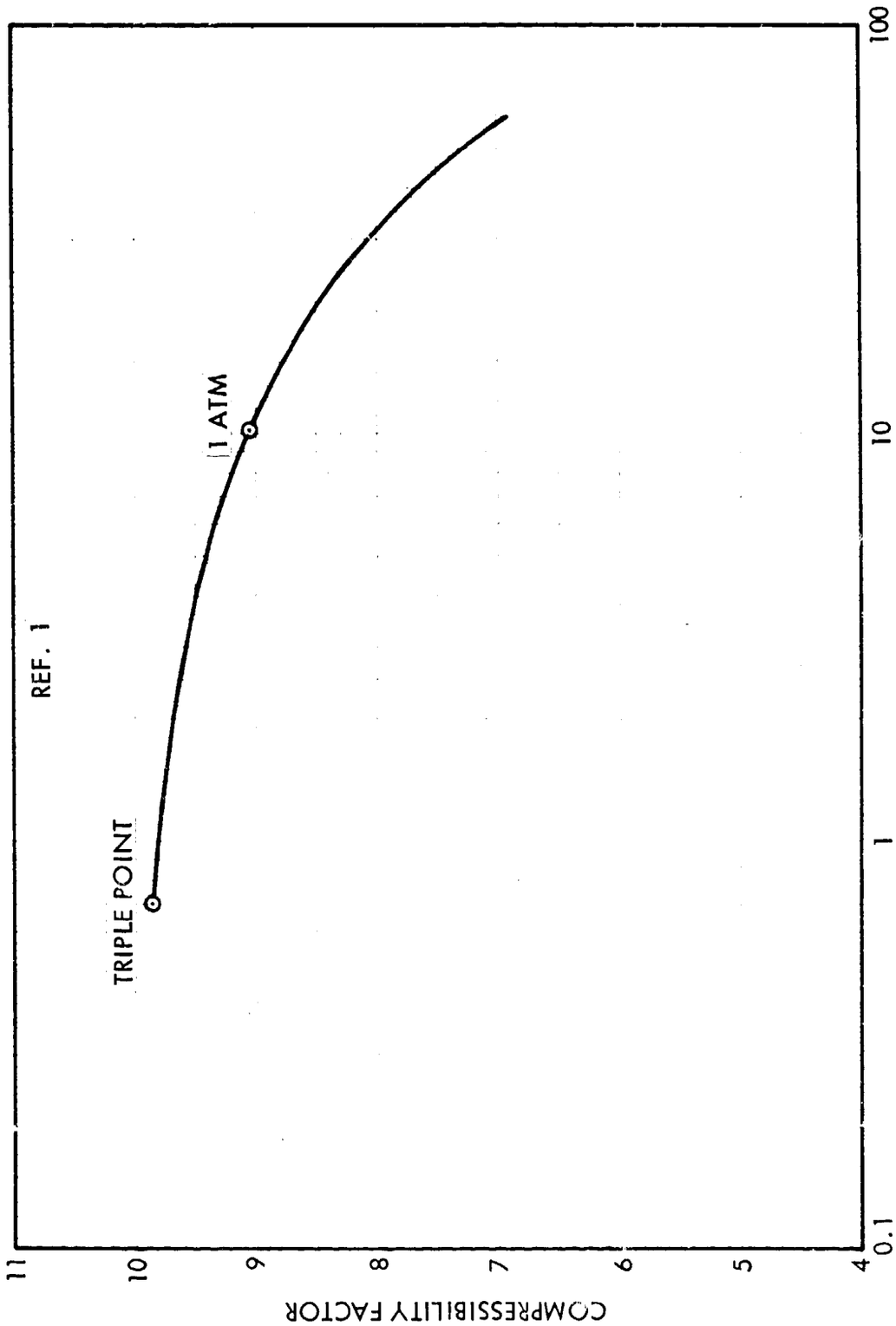

Fig. 3-32 Compressibility of Saturated Parahydrogen Vapor

Section 4

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Section 5

CONVERSION FACTORS

Multiply	By	To Obtain
Atmosphere (atm)	14.6959	Pounds per square inch (lb/sq^2)
Atmosphere (atm)	101325	Newtons per square meter (N/m^2)
British thermal unit (Btu)	1054.8	Joules (joule), watt-second (w-sec), or newton-meters (N-m)
Btu per hour-foot-^{o}R (Btu/hr-ft-^{o}R)	1.731×10^{-2}	Watts per cm-^{o}K (W/cm-^{o}K)
Btu per ^{o}R (Btu/^{o}R)	1898.6	Joules per ^{o}K (joule/^{o}K)
Btu per pound-^{o}R (Btu/lb-^{o}R)	4.18674	Joules per gram-^{o}K (joule/gm-^{o}K)
Btu per pound (Btu/lb)	2.32597	Joules per gram (joule/gm)
Btu per pound (Btu/lb)	4.6891	Joules per GMole(joule/GMole)
Degrees Kelvin (^{o}K)	1.8	Degrees Rankine (^{o}R)
Degrees Rankine (^{o}R)	0.556	Degrees Kelvin (^{o}K)
Feet (ft)	0.3048	Meters (m)
Joules (joule), watt-seconds (w-sec), or newton-meters (N-m)	9.481×10^{-4}	British thermal units (Btu)
Joules per ^{o}K (joule/^{o}K)	5.267×10^{-4}	Btu per ^{o}R (Btu/^{o}R)
Joules per gram-^{o}K (joule/gm-^{o}K)	0.23885	Btu per pound-^{o}R (Btu/lb-^{o}R)
Joules per gram (joule/gm)	0.42993	Btu per pound (Btu/lb)
Joules per GMole (joule/GMole)	0.21326	Btu per pound (Btu/lb)
Joules per GMole (joule/GMole)	0.4961	Joules per gram (joule/gm)
Joules per gram (joule/gm)	2.01572	Joules per GMole (joule/GMole)
Kilogram (kg)	2.205	Pounds-mass (lb-mass)
Kilogram per cubic meter (kg/m^3)	6.243×10^{-2}	Pounds per cubic foot (lb/ft^3)
Meters (m)	3.281	Feet (ft)
Newtons (N)	0.2248	Pounds-force (lb-force)
Newtons per square meter (N/m^2)	1.450×10^{-4}	Pounds per square inch (lb/in.^{2})
Newtons per square meter (N/m^2)	9.869×10^{-6}	Atmosphere (atm)
Pounds-mass (lb-mass)	0.4536	Kilogram (kg)
Pounds per cubic foot (lb/ft^3)	16.02	Kilogram per cubic meter (kg/m^3)
Pounds-force (lb-force)	4.448	Newtons (N)
Pounds per square inch (lb/in.^{2})	6.895×10^{3}	Newtons per square meter (N/m^2)
Pounds per square inch (lb/in.^{2})	6.804×10^{-2}	Atmosphere (atm)
Watts per cm-^{o}K (w/cm-^{o}K)	57.78	Btu per hour-feet-^{o}R (Btu/hr-ft-^{o}R)